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TITLE: DISCUSSION OF HIGH BRIGHTNESS RF LINEAR ACCELERATORS

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DISCUSSION OF HIGH BRIGHTNESS RF LINEAR ACCELERATORS

Introduction

Soon after electrons and ions were discovered, production of practical generators of particle beams began, and a succession of machines were invented that could produce more energetic and more intense beams. Progress on the energy frontier is often charted from the 1930's in the form of the Livingston Chart, Fig. 1, showing that particle accelerator energy has increased by a factor of about 25 every 10 years. The physics principles on which all of these devices work were deduced long ago; the energy increases were possible because of new types of accelerator circuits were invented, and because of cost reductions from thorough exploitation of parameters, engineering perfections, systems integration, and advanced manufacturing methods.

At the same time, the development of more intense sources proceeded. Linear accelerators (linacs) are suited to intense sources because the beam can easily exit the machine.

This discussion will concentrate on a particular kind of linear particle accelerator--the kind whose driving energy is provided by radio-frequency fields--that is well suited to producing high-brightness electron or ion beams. We will concentrate on the issue of high brightness and its ramifications.

Although technology to increase energy and intensity tended to be pursued separately in the past, recent applications have had to consider both, along with the ability to keep the beam very precisely confined, aimed, or focused. The figure of merit used is called <u>brightness</u>, defined (variously) as the beam power (sometimes only the beam current) divided by the phase space appropriate to the problem at hand. The beam energy for neutral particle beam defensive systems is selected to give

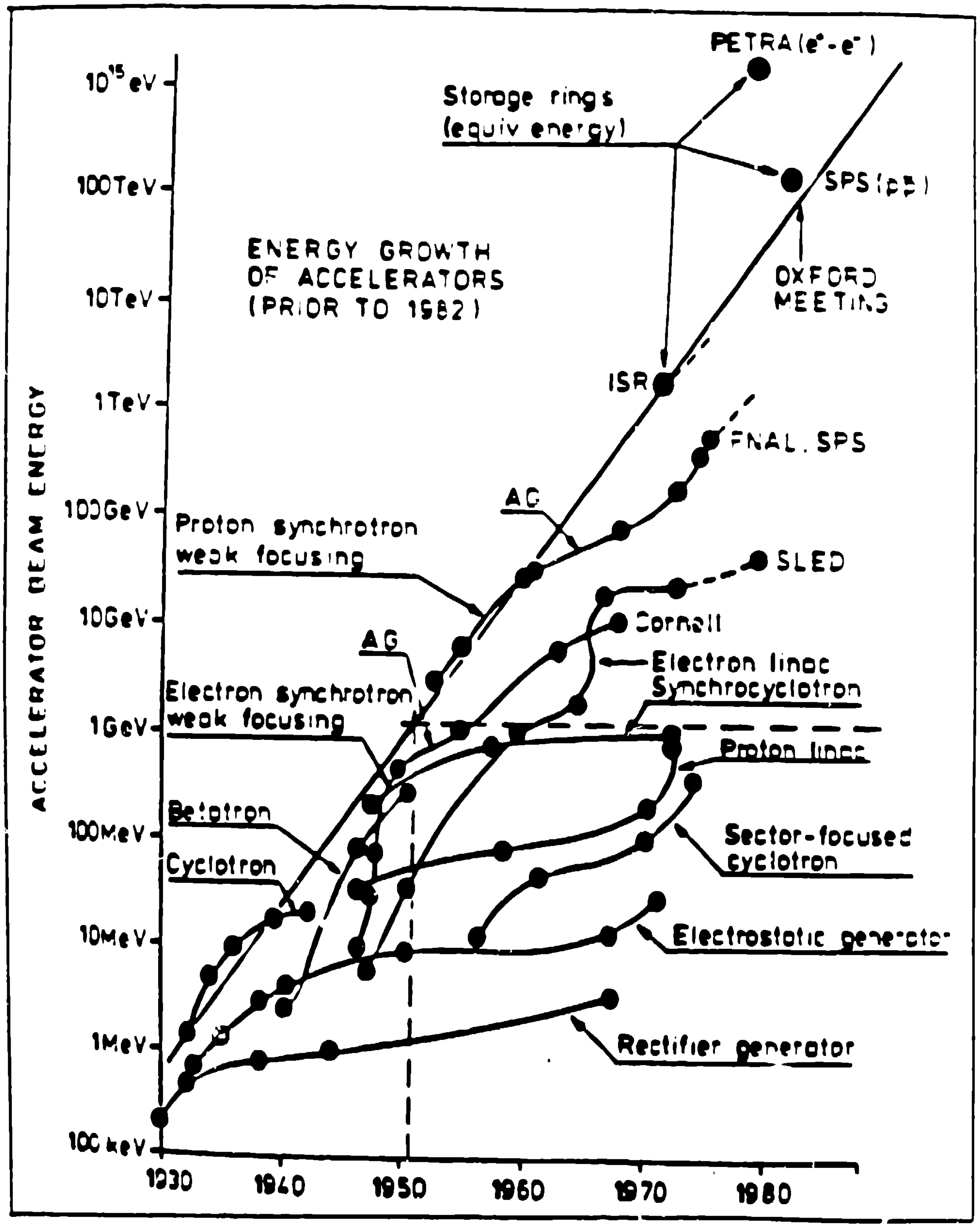

Fig. 1

The Livingston chart, showing the evolution of various types of accelerators with time.

Figure 1

the desired depth penetration at the target; with the energy thus fixed, the beam current becomes the relevant parameter in the numerator of the brightness equation. Phase space for the beam as a whole is six-dimensional, describing the physical size of the beam and the change in size with time or distance; the area projected on one plane is called emittance. Hitting a spot requires the beam power to be confined to a particular transverse area; if there are energy or time-dependent effects that are important to the application, then the longitudinal phase space must also be controlled. It is usually the average power that is of interest, whether to achieve an adequate data rate in a high-energy physics machine or to achieve the purposes of a defensive system.

Extrapolations in both the physics and engineering of rf linacs, as commonly interpreted in the accelerator community, are needed for today's advanced applications for physics research, defense, heavy-ion fusion, or materials-testing.

A calibration of the brightness requirements for these applications is instructive. In high-energy physics (HEP) research using colliding beams, the brightness requirement of the accelerator is combined with probabilities of events occurring in the physics experiment, in an expression called the luminosity. Long-range luminosity goals of 10^{33-34} $cm^{-2}s^{-1}$ at energies in the 3-TeV range are sought for electron colliders, compared to the design goal of 6×10^{30} $cm^{-2}s^{-1}$ at 50 GeV energy for the Stanford Linear Collider now under construction. Heavy-ion fusion (HIF) places severe requirements on a six dimensional peak brightness, thought to be achievable using multiple beams from induction linacs or rf linac plus storage-ring configurations. In Free Electron Lasers (FEL), the electron-linac brightness must match the requirements of the laser beam, and development is needed to achieve one to two orders of magnitude increase in full system brightness.

Neutral-particle beams penetrate inside materials, depositing their energy at a depth determined by the particle's dE/dx characteristics for the material. This penetration is a notable advantage of particle beams over photons because it is very difficult to harden against. Typical materials melt when exposed to around 1 kJ/g; with a penetration of 10 cm and nominal density of 2 g/cm^3, 20 kJ/cm^2 illumination is required, and for a 1-m^2 target, 2 x 10^8 J are required from the device. The Fusion Material Irradiation Test (FMIT) 80-MHz linac was designed for 100-mA average current (and achieved 50 mA at 2MeV before the program was canceled); thus, at the energy required for 10-cm penetration and 100-mA total beam current, with the 40% core of the beam on the target, one could get within a factor of 20 of the goal. However, if the target is far away, the angular divergence contribution to the brightness requirement is crucial. Again, the overall challenge turns out to be around three orders of magnitude in brightness.

So HEP, HIF, FEL, and NPB devices all have similar challenges and similar problems and approaches to solutions--the basic problems of attacking the numerator or the denominator of the brightness equation.
Unfortunately, the numerator and denominator are not independent.

Both high current and high quality require a detailed understanding of the physical limitations of the particle source and the subsequent accelerating and transport channels. Seminal progress has been made in this area in the past decade, requiring the extension of the classical accelerator physics to include plasma and collective nonlinear effects.

The particle source must be brighter than the final output requirement because the transport and acceleration processes can only result in preservation of the initial brightness, or more likely, in decreased brightness. Thus the theme of accelerator development is to provide a bright enough source, and to prevent excessive dilution of the source brightness as the beam is accelerated, within the basic physics engineering and economic constraints.

As the beam current is raised, nonrelativistic particles cease to be acted upon independently by the driving rf electromagnetic (EM) fields but begin to feel the repulsive force of the other, like-charged, particles, and the total EM interaction becomes the collective effect of the whole ensemble of particles and fields. The limit at which the particle self-fields cancel the externally applied fields, called the space-charge limit, is where control is lost of the acceleration and/or focusing process, a condition obviously deleterious to brightness. When high brightness is desired in the regime where space-charge is the dominant factor, scaling equations show that a higher rf frequency yields higher brightness; the current-carrying limit of the channel will decrease, but the achievable beam quality gets better (lower emittance) faster.

Requirements for continuous operation, however, argue for a lower frequency so that the components are large enough to lower the waste power density and facilitate cooling. This fundamental tradeoff results in a optimum frequency range of around 300-500 MHz for room-temperature structures.

If more beam power is needed than can be supplied by a single channel, then multiple channels could be provided. However, to maximize efficiency, it is clear that each channel should be operated as close as possible to the space charge or beam-breakup limits. With modern techniques of multiple-drive power sources and automatic control, the beam loading (ratio of the power actually delivered to the beam to the sum of beam power and the power required by the accelerating structure itself to establish the external fields) is high: 50% or more in room-temperature machines. Therefore, the cost of more beam power achieved by multiple channels is roughly proportional to the number of channels, although some savings can be obtained by engineering common rf field, vacuum, or cooling envelopes.

The numerator of the brightness factor could be raised by brute force, by using multiple devices or multiple beam channels, but then the supply power and waste heat removal requirements would rise directly, and so better system efficiency becomes a primary goal. High efficiency also means low weight and minimum volume when space basing is contemplated.

Similarly, the increase in beam brightness produced by reducing emittance requires care with each channel as well as consideration of whether and how multiple channels may be recombined. For example, channel constraints are more severe with low-energy ions; therefore, after initial acceleration, channels could be combined for better efficiency. Or, target considerations could affect the way the multiple-channel system is configured.

We thus begin to see that the brightness formula implies a host of system parameters and tradeoffs that affect the current and/or quality achievable and the price (in terms of cost, weight, or other factors) for achieving the desired brightness. Great care must be taken in defining the optimization problem because the imposed constraints can change the approach drastically.

Some considerations impose fairly strict boundaries with techniques or materials now available: for example, the maximum surface rf field achievable without sparking or the maximum magnetic field available from permanent-magnet material.

Particle Sources and Preaccelerators

The process starts with ion liberation into vacuum by the thermal or laser excitation of a surface or a gas. For NPB devices, a "surface-type" ion source invented in the USSR has been successfully developed to produce a negative hydrogen ion beam with high enough brightness to fill a single accelerator channel. Although it works, the physics of this source is not well understood, and it also needs further development to improve its stability, reliability, and eventual ability to operate continuously. Unsuccessful attempts to find other suitable emitter materials emphasize the need to continue work on understanding the physics of such sources.

A new type of "volume" ion source in which the ion production occurs by reactions in the open volume rather than on the surfaces, promises good operating characteristics and continuous operation but so far has not shown adequate current density and emittance.

The beam to be accelerated must be formed by extracting ions in a very precise way from the source region; this is done by applying a voltage on aperture plates. In the extraction region and beyond to the entrance of the preaccelerator, both the physics and the interaction geometry are very complicated; the physics because the presence of other ions and electrons changes the production rate or changes (neutralizes) the net charge of the desired beam. The geometry is basically three-dimensional and thus not amenable to detailed computer modeling and design, meaning that development work must be largely done experimentally.

The continuous beam from the ion source must be carefully bunched and "matched" to an rf accelerating wave and brought to higher energy. The space-charge forces and nonlinear field effects during this process tend to spoil the initial beam quality.

The preferred preacceleration techniques for ions is to shape and accelerate them gently, nearly adiabatically, to preserve the beam quality. This is done in a relatively new USSR invented device called the radio-frequency quadrupole* (RFQ) accelerator, a structure that basically provides a powerful electrostatic focusing field that is carefully perturbed to provide a longitudinal accelerating field component. The RFQ captures a high percentage of the input particles and delivers them to the main accelerator properly bunched with minimal degradation of the source quality. The development of the RFQ is a major landmark in ion linac technology, fundamental to the achievement of high-brightness beams.

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*RFQ is the Western name: the Soviets originally called it "Spatially Uniform Quadrupole Focusing," they now use either term.

Rf Linacs

Upon leaving the RFQ at energies around 2 MeV, ion beams are further accelerated in the traditional drift-tube linac (DTL) structure. This structure's electrical efficiency decreases as the particle energy increases, so at energies around 100 MeV, a change is usually made to another standing-wave circuit called the side-coupled linac (SCL) structure, which has increasing efficiency with particle energy. (The efficiency transition has a broad overlap, and the DTL could be used up to a few hundred MeV depending on rf power requirements and other system trades.) The ion beam is only traveling at about 40% of the speed of light at an energy of 100 MeV, so it is still nonrelativistic and influenced by space-charge effects at the desired energies of a few hundred MeV. Therefore the strategy of slow, nearly adiabatic changes is pursued in the beam dynamics design through the entire ion linac.

Beam Transport

Upon leaving the accelerator, the ion beam is transported through the next stages in its intended use. Further precise manipulations of the beam emittances are required in these transport regions. For example, the beam orientation and divergence or convergence must be made proper in the transverse planes for the desired operation of an NPB output telescope. The longitudinal properties are also adjusted through the use of electrostatic bunchers that apply rf fields to make the beam bunch even more tightly or to cause the beam to debunch into a dc beam, as the case may be. To achieve the desired results, chromatic and geometric aberration effects from nonlinearities in the external electromagnetic fields have to be minimized to prevent brightness degradation. Space-charge effects are still present for the ion beams, and these interact with the aberration effects. Design is not completely amenable to present analytic or computer simulation techniques, so extensive experimental tests are required.

Rf Power

The rf power systems required for space-based NPB have only very recently received any attention, despite the fact that they are a major system component. Since the time that radar systems turned toward phased arrays, little development of compact, high-power, high-efficiency rf systems has occurred, except in Europe, where advanced cw and high peak power klystrons have been built. Work is beginning to close this gap, but there is much to be done. Ultimately, several hundred megawatts per device of cw or long-pulse power will be required. We are most interested at present in frequencies around 400 MHz with high efficiency, low cost ratio ($/W), and for space-based systems, high weight (W/kg) and volume (W/cm^3) ratios. Extant klystron systems have modest efficiencies around 55%, low weight and volume ratios, and require high dc drive voltages; thus they are not attractive for space-based rf power, but they show promise for development to efficiencies around 70% at good cost ratio and are the chosen approach for large, ground-based FEL systems. Gridded tubes have low gain and filaments, resulting in overall efficiencies around 50%, and extrapolate poorly to future requirements because of plate dissipation limitations. Two new sources are under study; the first is solid state, with the recent demonstration of a 2-kW, 1-ms pulse length, 10% duty factor, 80% efficient module that could be combined in a 500-kW amplifier module with prime power-to-rf efficiency of about 55%. The weight ratio at present is about 1320 W/kg with about 2200 W/kg on the horizon. The Eimac/Varian klystrode is another possibility, more compact than a klystron because it uses a gridded interaction region with a klystron-like output cavity and collector. Tubes are available for 25-kW, cw, UHF-TV service and should scale to a few hundred kilowatts cw. Contrary to solid state, where volume and weight scale directly with power, the klystrode tube size would increase about 20% as the power is doubled. The dc-to-rf efficiency of the klystrode is about 70%, but the gain of about 23 dB still requires a high-power driver. Magnetrons and crossed-field devices are not sufficiently phase stable for accelerator service at present.

The rf linac power systems require further development of the control systems that provide dynamic stabilization of the rf field amplitudes and phases in the accelerator structures. Tighter control, to better than 1% in amplitude and 1° in phase, is required, with broader closed-loop bandwidths to a MHz or beyond. The structures must be kept on resonance, and the multiple rf sources driving one accelerator tank must be synchronized under a variety of working conditions.

Automatic Control

Full automated control of SDI devices is required over their entire operating life, from deployment through standby, turn-on, and operational phases. Modern linacs have extensive control systems, many of which, like the rf field controls, are fully automated. The computer-based data collection and command systems, however, are largely supervisory in nature and require human operator decision and action to close the loop. Some hardware systems, like the ion sources and injectors, are as yet hardly automated at all. Controls development is thus a primary objective and must be a primary consideration in the trade-off decisions. Work has started on the automation of various subsystems, notably the injector, and on the overall architecture for system control. The combined use of the detailed computer simulation models available for linacs, powerful nonlinear constrained optimization techniques, and artificial intelligence techniques is under development. As stated above, closed loop control of rf parameters is important, as is control of ion source variables. Precision output beam positioning requirements place tighter tolerances on all aspects of mechanical or electrical systems that could produce position or energy jitter in the beam; it will be necessary to understand and control mechanical vibration spectra better than ever before.

Engineering and Economics

Significant engineering development has occurred in the past decade which points the way toward linac systems with power/weight/mass properties feasible for space exploitation. A great deal of engineering work remains to be done. The linacs must provide the electromagnetic fields as required by the beam dynamics, with maximum power, weight, and volume efficiency, reliably and with essentially no operator interaction.

Power efficiency has several aspects, several of which, such as the use of multiple channels and improved rf sources, were noted above. Another research area involves achieving higher peak surface fields in the accelerator structures before the breakdown level is reached. Higher fields translate into higher beam current limits; for example, in the RFQ the current limit scales as the accelerating gradient to the five-halves power, so the incentive to increase the field is strong. Further, a higher accelerating gradient on-axis would result in a shorter linac, but a higher accelerating gradient requires more rf power and also makes more difficult the engineering problems of waste heat removal. This is one of the most fundamental of linac design engineering tradeoffs. The point of view taken must begin with the fact that cw operation is ultimately required; this limits the linac gradients to a few MeV/m with present practice.

Summary

The fundamental aspects of high-brightness rf linacs have been outlined to provide a perspective for evaluating USSR R&D in this area of accelerator technology. The discussion shows the breadth and complexity of the technology and indicates that synergism with advancements in other areas, such as rf power development, is an important consideration. Analysis of the devices also requires an assessment of the available theoretical and computational tools used for analysis and design.

ION SOURCES/INJECTORS

Laser Driven Ion Sources

Since 1980 at least, there has been continuing interest in the use of laser activation to produce ion beams of any element, with up to 10^{11}-10^{12} multiply charged, or 10^{15}-10^{16} singly charged ions per pulse. Current densities of 10-40 A/cm^2 are discussed for 1-5 kA beams at 150 keV and pulse lengths of 100-200 ps. These pulse lengths are too short to be of interest for high duty machines, but if the generation techniques prove feasible and the intrinsic brightness is high enough, extension to higher duty factor could follow. These sources provide more than enough raw current to saturate an rf linac channel; therefore scraping or cooling techniques might be applied that waste even a large fraction of the current but might provide adequately bright beams for injection into a linac. At the 1986 XIII International Conference on High Energy Accelerators, ITEP announced the reconstruction of their proton synchrotron to also accelerate heavy ions. [ABVLKLNOSCV 1986]. The ion source will use a 200J CO_2 laser to produce ions with $Z/A \geq 0.1$.

Beam cooling

The 1977 paper by V. A. Batalin is a very competently done analysis of the possibility of applying electron cooling to proton (H^+) beams; it clearly shows full comprehension of all the complex issues regarding this possibility. Although there is no discussion of the feasibility of cooling H^- beams (which unfortunately would have the same sign as the electron, so the techniques described will not apply directly), similar arguments apply concerning the need for neutralization and so on. The desirability of such cooling at the low-energy input to a linac has been evident but so far a practical technique has not been invented. It is not clear that Batalin's ideas were ever carried into the experimental stage--although there would be formidable difficulties in achieving a stable and uniform interaction, the research would be a valuable contribution to the understanding of the interactions of low density beams undergoing weak-plasma mixings.

RF ACCELERATOR STRUCTURES

Different accelerator electromagnetic circuits must be used as ion beams are brought up in energy. This is because low-energy ion beams are non-relativistic and their velocity increases as they are accelerated. In the rf linac, the rf wave always repeats its period in the same interval of time, and the ion must be exposed to the accelerating field in the proper manner--either in synchronism with an rf wave traveling along with the beam, as in the RFQ, or at precisely the right time during each cycle (and hidden during the wrong times) as in the DTL and CCL. Because the particle is speeding up, it travels further each cycle, and at some energy in a particular circuit configuration, the "cell length" (the distance traveled in an rf cycle) becomes inefficiently long in terms of both physical length and the rf power required to drive the cell. The RFQ is efficient (for protons) for energies between about 50 keV and 2 MeV, the DTL from about 750 keV to 100 or 200 MeV, and the SCL from 100 MeV on; in fact the SCL efficiency increases with energy. The physical principles are much the same in these three structures; the engineering has many overlaps but also substantial differences. Other types of structures have been proposed, such as the Alternating Phase-Focused (APF) structure, or are constantly being sought to find a better optimum for some application. For example, structures that would allow higher operating acceleration gradients, or higher shunt impedance requiring lower rf power input, or better vibration characteristics, or with better engineering characteristics, would all have significant impact on overall system design.

In this section, work specifically related to actual structures is analyzed, including theoretical and computational work but particularly experimental work where hardware is being constructed and tested. Later, in the Beam Dynamics section, theory and computation from the more fundamental point of view of high-brightness beam generation will be discussed.

<u>Structures for Ion Energies ~ 50 keV to 2 MeV</u>

Traditional linacs used the idea of building a resonant rf cavity that would provide the correct longitudinal field at the proper intervals to accelerate particles and shield the particle from the field during the remainder of the cycle. This is accomplished by nanging drift tubes in a cylindrical cavity; the field is established across the gap between drift tubes, and the beam is shielded by passing thru the drift tube. This DTL structure is still used from around 750 MeV to 100-200 MeV and is discussed further in the next section. It is intrinsically an accelerating structure, and if each gap is located to provide an accelerating field, the particle beam will be unstable radially and the transverse size would increase. Therefore, external transverse focusing field has to be provided; this is done by installing quadrupole magnets inside the drift tubes. By alternating the polarity of the quadrupoles, a strong-focusing system results that keeps the beam focused transversely. However, the required magnetic strength increases and the drift tube length decreases with lower particle energy, with the result that sufficient focusing strength using electro or permanent magnet techniques cannot be packaged into a drift tube at particle (proton) energies much below 750 keV. The classical preaccelerators to bring the beam up to this injection energy were very large and cumbersome Cockroft-Walton dc accelerators.

It had long been desired to reduce the size and complexity of this "front end." One possibility studied in the USSR and elsewhere attempted to use the fact that, at other phases along the rf cycle, various combinations of longitudinal acceleration/deceleration plus transverse focusing/defocusing occur. By systematic alternation of the location of the drift-tube gaps, stable acceleration plus focusing without the need for quadrupole magnets could be achieved. However, this procedure, called alternating phase focusing (APF), required a relatively longer structure and the stability region was not as large. Thus when another circuit, the RFQ, was invented which did not have these disadvantages, APF was abandoned in the West. In the USSR, interest remained at KhFTI, where more intricate variations showed promise (around 1982) for asymmetric APF (AAPF) schemes that could reach beam current limits of the same order as were being demonstrated by the RFQ. It is of interest to see if recent publications show that the AAPF schemes were successful in practice.

The radiofrequency quadrupole (RFQ) circuit begins with a different premise--to first provide transverse strong-focusing using a time-varying rf electrostatic quadrupole field along the beam axis, and then perturbing the transverse field to introduce longitudinal components for bunching and accelerating the particles. In this case, the transverse focusing force is independent of the particle energy, and powerful focusing can be provided down to typical ion-source voltages of 10's of keV. RFQ's are thus characterized by four electrodes along the beam-axis, whose surfaces are modulated with a period corresponding to the particle energy. At low energies (10's of keV), this period is short (of order a few mm), and many cells can be used in a structure of reasonable length, with only a small change in each cell serving to nudge the particles into bunches and accelerate them. With this approach, almost adiabatic, the particles are maneuvered very gently and can be brought to an energy (protons) of around 2 MeV with very little degradation of the source brightness. In contrast, the traditional system of injection directly into the DTL typically cost a factor of ten or more in transverse brightness. Further, the RFQ system has an attractively high beam current limit, and is much smaller and more reliable. Therefore, rapid development occurred from 1978 on in the West, and the Soviet Union, which invented the concept but developed it little before 1978, presently has a full capability in RFQ's as well.

RFQ development toward high brightness applications has been spearheaded in the West at Los Alamos; many RFQ's have now been built around the world but almost all of them accelerate low beam currents of various ions where space charge effects are negligible. After conducting the first proof-of-principle test in 1980, Los Alamos has explored the current limit of the RFQ, exploitation of the structure up to the 2 MeV energy where inefficiency dictates handoff of the beam to the DTL (now easily realized in terms of the focusing), and engineering to high duty factors including cw. The present demonstrated capability of high-brightness RFQ's, sufficient to argue convincingly for the feasibility of continued development toward space-based NPB systems, results from only <u>two</u> RFQ's, the pulsed 100 mA, 100 keV-2 MeV, 425 MHz ATS proton RFQ, and the cw, 75 keV-2 MeV FMIT deuteron RFQ which was designed for 100 mA and achieved 50 mA cw before the project was terminated. Although essential engineering experience and much valuable data were gathered from this FMIT RFQ, funding was cut off at the point when the most important and fundamental beam-dynamics information relative to high-brightness was ready to be gleaned. On the ATS RFQ, the internals were replaced several times but funding restrictions prevented true iterations that would allow integrated experience to be exploited. In the assessment of the open literature below, we can see that equivalent reported progress has been made in the USSR; one can easily speculate that substantially more unreported capability could exist, given the knowledge that the Soviets are capable of being serious about their research objectives.

A very well-written baseline report, "Radio Frequency Quadrupole and Alternating Phase Focusing Methods Used in Proton Linear Accelerator Technology in the USSR," Nikita Wells, R-3141-ARPA, Rand Corp., January 1985, exists for the work done up to 1982 and should be considered an essential part of this report, to avoid rewriting.

Alternating Phase Focusing

Cold model tests on a seven-beam multiple channel, AAPF structure for heavy ions was discussed at the 1980 USSR 7th All-Union Conference. [GGGNSSKPF 1980] The structure, shown in Fig. 2 is called a "story" type based on a two-conductor line, and is based on Ar^+ at an injection energy of 3.1 keV/n; length is 0.8 m, diameter is 0.3 m, the operating frequency is 50.6 MHz, and the longitudinal acceptance is about ± 30° by ± 1.6% $\Delta\beta/\beta s$.

MPEI [BVGGGNNMSS 1982] continue their work using multiwire resonators to realize interleaved DTLs, RFQs, and FWF k=3 structures, (see definition below) using APF principles, and pointing toward heavy-ion applications. Various structures are shown in Fig. 3. In the middle, an annular beam would be accelerated within the space between the two closely spaced cylinders at about half the outer tank radius, in a drift-tube system with APF focusing. They are working on multi-beam systems (a 7-beam model is cited and a four-beam RFQ is shown at the bottom of Fig. 3.) In this area they are well ahead of the U.S., where funding agencies have

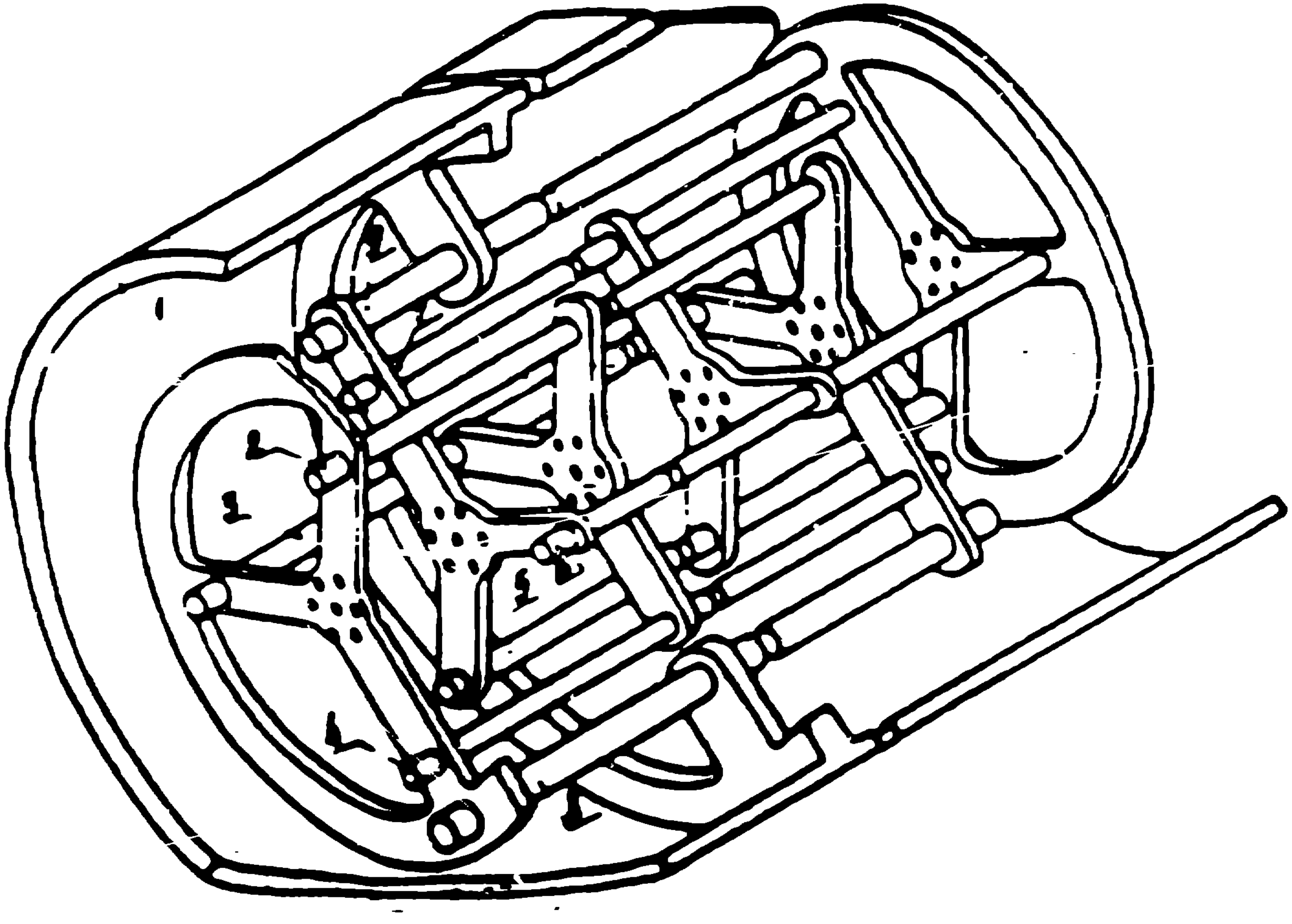


Figure 1. Accelerating Structure of "Story" Type Based on Two-Conducting Line

Pages 9-10.

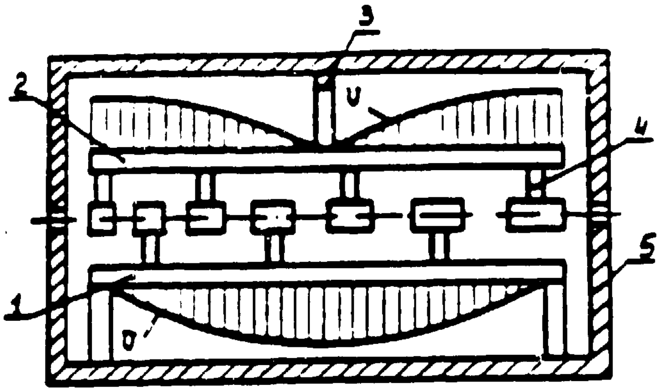
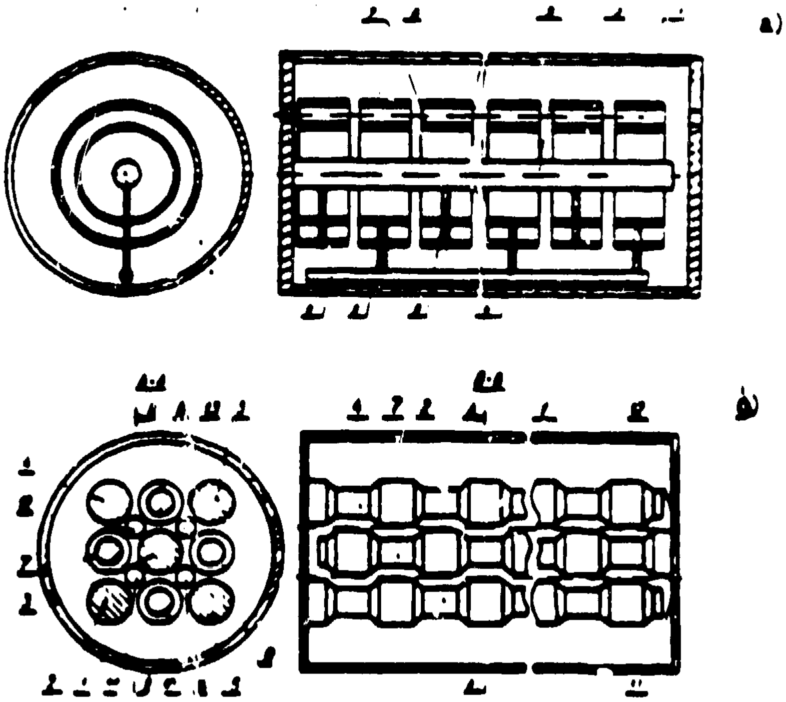


Fig. 1. Half-wave double-wire resonator.



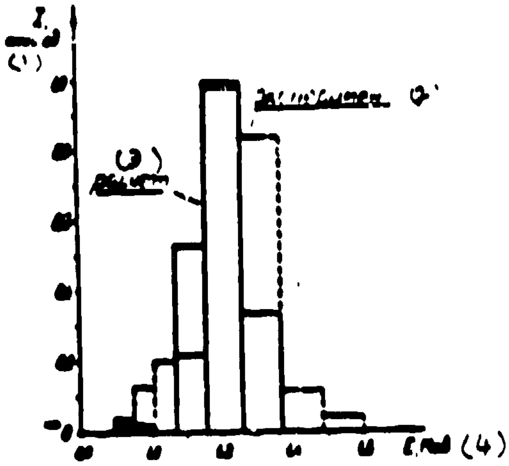


Fig. 2.

Fig. 3.

Fig. 2. Multichannel accelerating structures: a) coaxial cavity with circular span channel 1 - span channel; 2 - resonator; 3 - center conductor, 4, 5 - strut; 6, 7 - cylindrical electrodes; 9 -

concentrated on nearer term objectives. A companion paper [LPPS 1982] concerns analysis and design methods for multiwire line structures.

The spiral-loaded structure is another type of resonator useful for acceleration of low-energy ions. The 1984 9th All-Union shows development of such structures by MIREEA and MPEI [VGGKKLLLMIMBV 1984] as part of their work to create families of accelerators suitable for national economic and research needs; the spiral structures have the desired "consumer" qualities of small overall size, high efficiency and cost-effectiveness, simplicity, reliability in operation, and modularity of design. Injection energies are around 100 KV/ion, and the structures are variable frequency to allow a range of ions to be accelerated: (150 MHz for protons, down to 37.5 MHz), or to some extent, the accelerating gradient can also be varied. Examples for acceleration of low-current (1.5 mA) deuteron beams to 3 MeV are given. Focusing is achieved by APF. Structures are described that have a variety of field distributions, such as a step or ramped voltage increase. The Science Research Institute of Physics and Optical Measurements, Moscow [PSSF 1984] also reports on a compact proton accelerator for 1 MeV, 5 mA of protons using a quarter-wave spiral coaxial resonator with drift tube, and direct coupled to the rf drive tube.

Several journal articles also give evidence that MEPI and ITEP continue to have an interest in APF machines, particularly for small machines with possible industrial applications. [AABVVGGGDZKMNNPRSSTS 1983, BGR 1984, AABVVGGGDZKMNNPRSSTS 1983, KKS 1983, KKKS 1984]

Radio Frequency Quadrupole (RFQ)

A vital engineering area of RFQ development for high duty factor or CW operation concerns providing water cooling to the RFQ vane area where this is little room. At KhPTI [BDP 1978], the techniques for boring deep holes accurately using active control were being investigated in the 1978 time period.

Discussion at the 1980 7th All-Union of an RFQ for the MEGAN dealt with space charge effects for 50-100 mA beams with input emittances 3-8 times larger than those sought on the ATS, and emittance growths of factors of five are reported for the 90% beam contour. [VVYOPSC 1980]

The INR group had also written a program to calculate three-dimensional electrostatic fields in a modulated four-line structure with random electrode shapes using an algorithm based on integrated equations with sources shifted deep into the conductors, and achieving an accuracy of better than 1%. This program was used to optimize electrode shapes and study the field and capacitance distribution along the structure.

It is interesting, perhaps ironic, to note that in the 1980 7th All-Union Conference summary (Part II, page 545), some pride was taken in stating that "in the field of developing new accelerator structures, the Soviet specialists have the leading place in world science --- asymmetrical alternating phase focusing, RFQ, DAW---."

ITEP [AABVDKK, ET AL. 1982] announced the commissioning of their pulsed proton prototype 148.5 MHz RFQ at the 1982 8th All-Union meeting. It is stated that the accelerated current did not exceed 50 mA, and that the problem of increasing it (further) "did not relate to the primary;" so there was some kind of problem but its nature is unclear.

The operating details of an RFQ of the split-coaxial type are described by IHEP [ZIKMMNST 1982] at the 8th All-Union, 1982. Experiments were conducted using two preaccelerators, one a 0.51 - 3.26 MeV linac, and the other a 0.1 - 0.635 MeV section. Input beam emittance was varied over the range 0.1-0.3 πcm•mrad (normalized, 90% contour) by changing the source geometry. Although they say that the split-coaxial structure is structurally simpler than the four-vane shape, Western workers and also ITEP have stayed with the four-vane shape. Currents of 100-150 mA were accelerated to 2 MeV. Output $\Delta p/p$=1.7%, compared to 1.9% calculated. The output normalized emittance at the 90% contour was not more than 1.0π cm•mrad, but it is stated that the input beam was not matched.

Kapchinsky [K 1982] describes a program to construct a 70 MeV, 5 mA average current proton accelerator for radiation damage studies of fusion reactor materials. The machine would accelerate 150 mA peak currents in 100μs pulses, using a 62 keV injector, an RFQ and a DTL. The RFQ required is the same as planned earlier and commissioned as described above.

At the 1983 U.S. Particle Accelerator Conference, Kapchinsky ITEP [KAABCDEKKKKKKLSUV 1983] reported on the fabrication and operation with protons of a 3 MeV 150 MHz RFQ at 100 mA, 25 μs pulses. The structure is 4.9 m long, and made in eight sections. Tuning plates allow a resonant frequency change of ± 1.5%. Four rf drives are used, one in each quadrant, and it is stated that this produces a loaded Q=4700 and enables field adjustment such that unwanted dipole components are below 2%. The longitudinal field is flat to within 10%, but 100-150 μm vane movements were sufficient to upset the magnetic field distribution, so ITEP had discovered, as had Los Alamos, that the accuracy requirement on vane placement from the point of view of high-frequency resonator tuning is more stringent that the requirements from tolerances on transverse field distortions. The use of vane coupling rings to help stabilize the transverse fields in this electrically long structure were not mentioned at this meeting, but were mentioned the following year at the 1984 Linear Accelerator Conference in Kapchinsky's review of the history of RFQ's. ITEP had also decided to use a constant radius of curvature for the vane tip modulations, leading to reduced peak surface fields (or conversely the ability to run at higher fields). During rf conditioning, they observed that sparks tended to occur between vanes or at the gap between longitudinal sections. Performance with the protons beam agreed with calculations. The device is shown in Fig. 4 (Fig. 1983 PAC). By way of comparison, this ITEP RFQ was, at 150 MHz, an intrinsically lower brightness device than the Los Alamos 425 MHz ATS RFQ and also easier to tune electrically because of the lower frequency. No emittance figures are given for the ITEP RFQ.

It is interesting to note that four papers [GLVK 1984, LK 1984, BKKLKS 1984, B 1984] were submitted as abstracts to the 1984 Linear Accelerator Conference in Darmstadt, Germany (and tagged by the CIRC database), but were withdrawn before the meeting. These papers covered input matching, mode frequency computations, and discussion of space charge effects and emittance growth -- the latter especially important to high-brightness

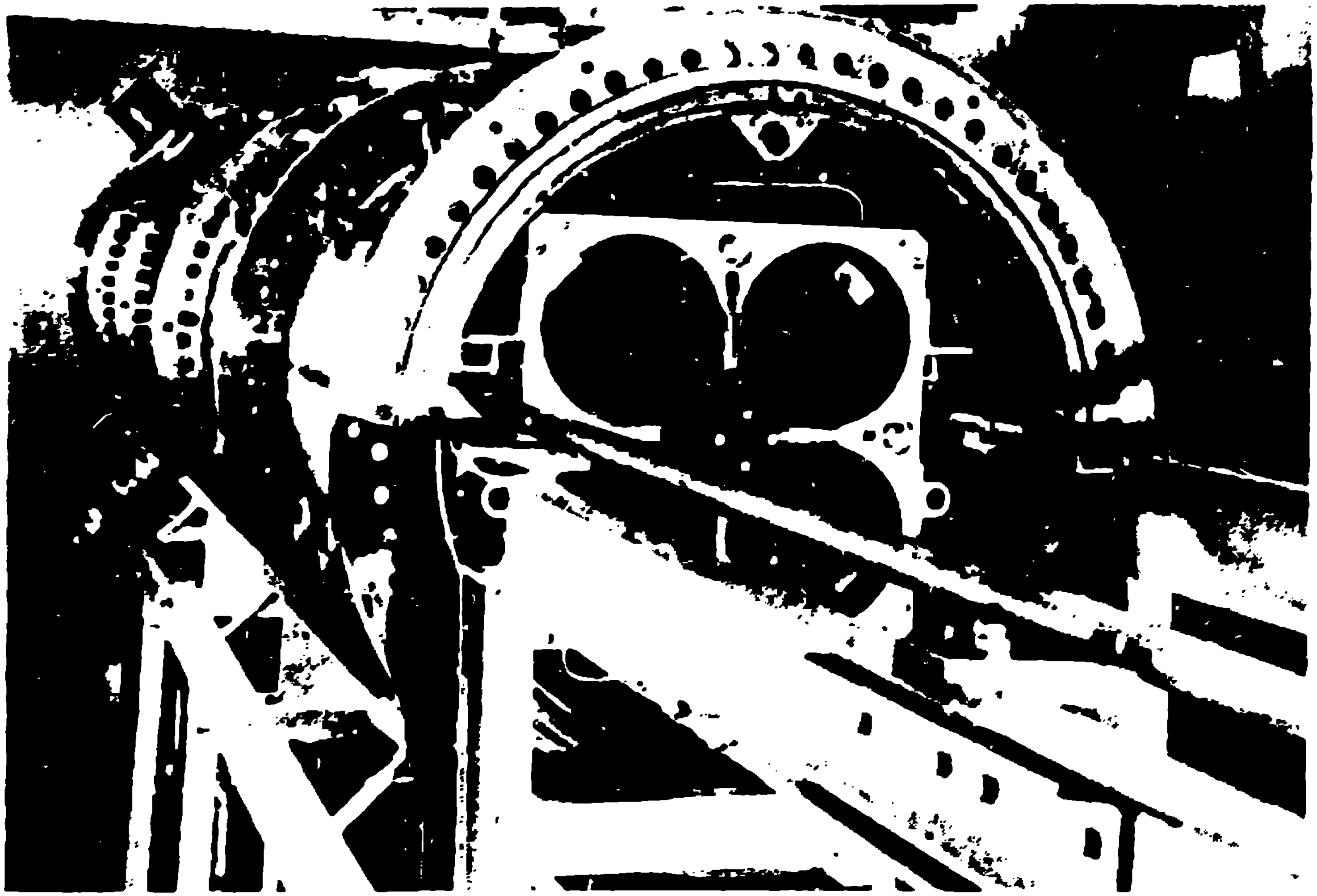


Figure 4

Fig.4. The RFQ Linac resonator in a vacuum tank.

RFQ's. However, we have these articles as preprints that were handed out at the meeting, if memory is correct [GL 1983, LH 1983, BKKL 1984, B 1982]

Activity on RFQ's at two institutes is reported at the 1984 9th All-Union. The ITEP team discusses the use of vane clamping rings in detail, [VVGDDKU 1984] and the problem of keeping the RFQ on resonance during operation. [ABDKU 1984] Resonance tuning is complicated by the four-chamber nature of the RFQ, requiring equal adjustment in each. Using movable plates in the end regions in the 5 m long 150 MHz structure, they obtained a tuning range of 60 kHz, twice as much as the anticipated departure from resonance expected from water temperature variation, with variations in field between chambers of 8-13% but averaging only 3% overall. Using an automatic control loop, resonance is maintained to ± 100 Hz.

ITEP also reports on a physically large RFQ operating at 6 MHz for accelerating heavy ions. [DDZKKNPU 1984] The device, Figs. 5A and 5B (9th A. U. VI, PI, pg 502-03) is 6 m long and 1.2 mm in diameter, with a four-wire line supported by tri-radial spiral inductive supports. Acceleration is from 212 keV/n to 2.14 MeV/n. Studies of heavy ion linacs for fusion drivers are concerned with handling very high ion-beam currents (for delivering high power to the target) and very low beam emittance (to achieve a small focal spot at the target). Thus, research on heavy ion fusion (HIF) (or TIS, in the Russian acronym) drivers is concerned with similar frontiers in beam physics as is the neutral particle beam research. The study of HIF at ITEF dates to 1979, according to Zendevich et al. (1983), and addresses driver design, linac development, high-brightness source design, and beam dynamics for high-current beams. Travelers to the 1986 Novosibirsk Conference on High-Energy Accelerators report that perhaps ten people are thinking about the problem at ITEF (whether part-time or not is not known and, certainly, this number does not include the technicians in the hardware program).

One driver design [ZIKKS 1982, KZ 1981] is novel. Heavy ions in a high charge state ($q \approx 10$) are accelerated in an rf linac, then allowed to suffer charge exchange with a colliding beam of

H^- ions until they decrease their charge state to q = 1, whereupon they are stored and bunched for delivery to the target.

INR contributes a detailed analysis and numerical study on the form that RFQ electrodes should take [BVC 1984], and a complicated discussion of what would happen in a heavily beam-loaded RFQ if the field were not automatically controlled to compensate for the loading. [BS 1984] Since field compensation is standard practice, this result is not particularily useful.

At the 1986 XIII International Conference on High Energy Accelerators, ITEP [KKSABVDDZIKKLLPPSU 1986 - (abstract)] says that the 6 MHz, Bi^{2+}, 2.5 MeV RFQ was constructed and was brought to the design electric field. The rf-linac driver concept described by Kapchinskij et al. [KKLSABDYIKKLPPSUA, 1986] is very similar to those studied for years in the West, consisting of a tree of linacs starting with 16 in parallel, whose outputs are combined successively in pairs until the resulting high-current beam is injected into the main Alvarez linac (200 MHz). Since the frequency is raised by a factor of two or more at each combining stage, the frequency in the initial linac is very low, 6 MHz. They have completed a prototype of the first RFQ at this frequency and have succeeded in accelerating 5 mA of doubly charged xenon ions to an energy of 1.35 MeV with a capture efficiency of 70%. The structure is substantial in size (6 m long) and the low frequency (6 MHz) posed some special fabrication problems especially in connection with mechanical resonances. The electrically resonant structure chosen consisted of four specially modulated conductors mounted on spirals made from copper tubes. The mounting was tricky because of the need to avoid mechanical vibration. A highly efficient heavy-ion accelerating structure is mentioned in a title [B 1986 (Sess.3.10)] at the 10th All-Union. Another mention of acoustic performance (probably induced vibration effects) due to the pulsed rf is made [K 1986 (Sess.4.14)]; such effects would be important in systems such as NPB where the output beam must be pointed very accurately. [B 1986 (Sess.4.17)] discusses a low injection energy structure for a proton linac.

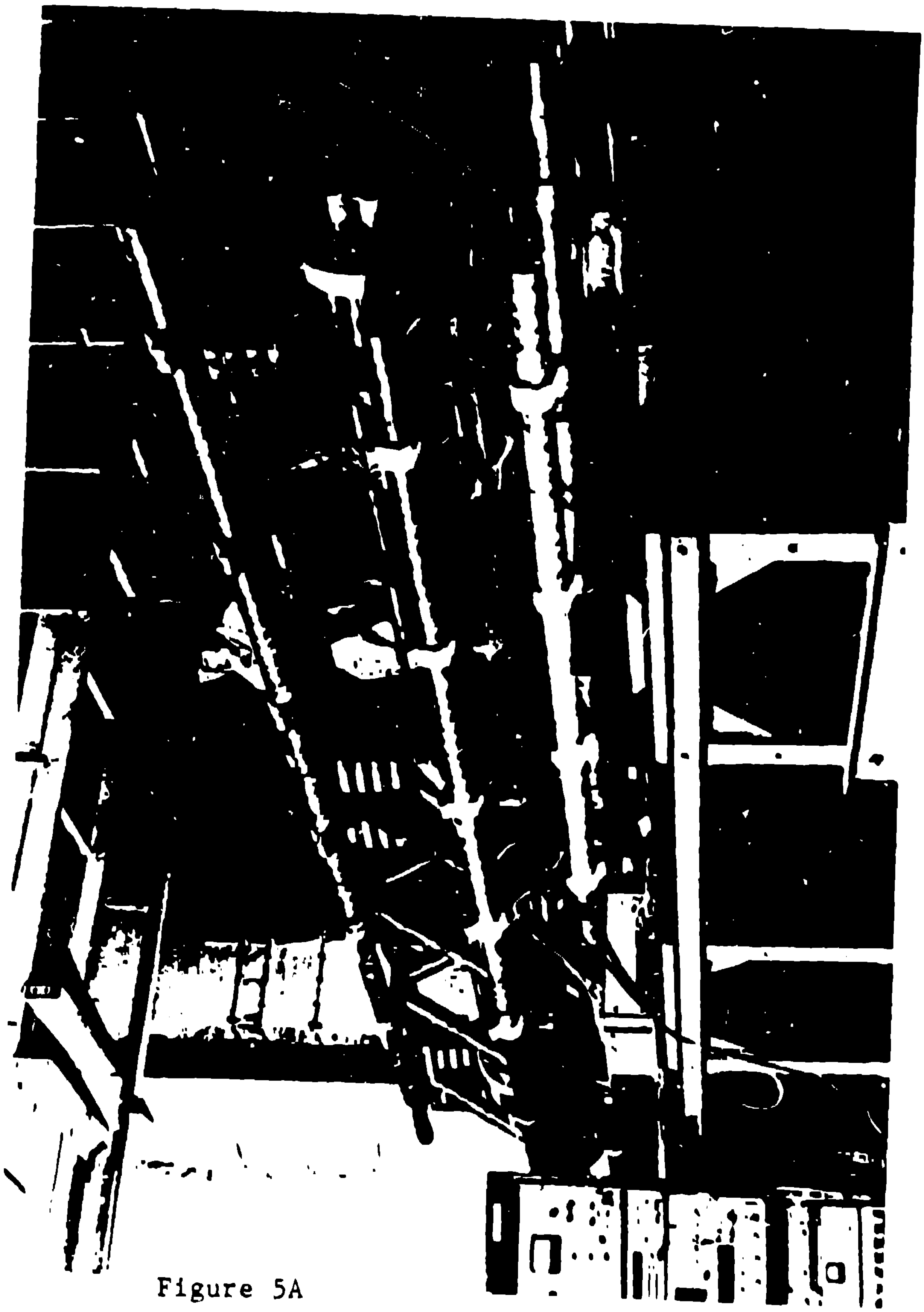


Figure 5A

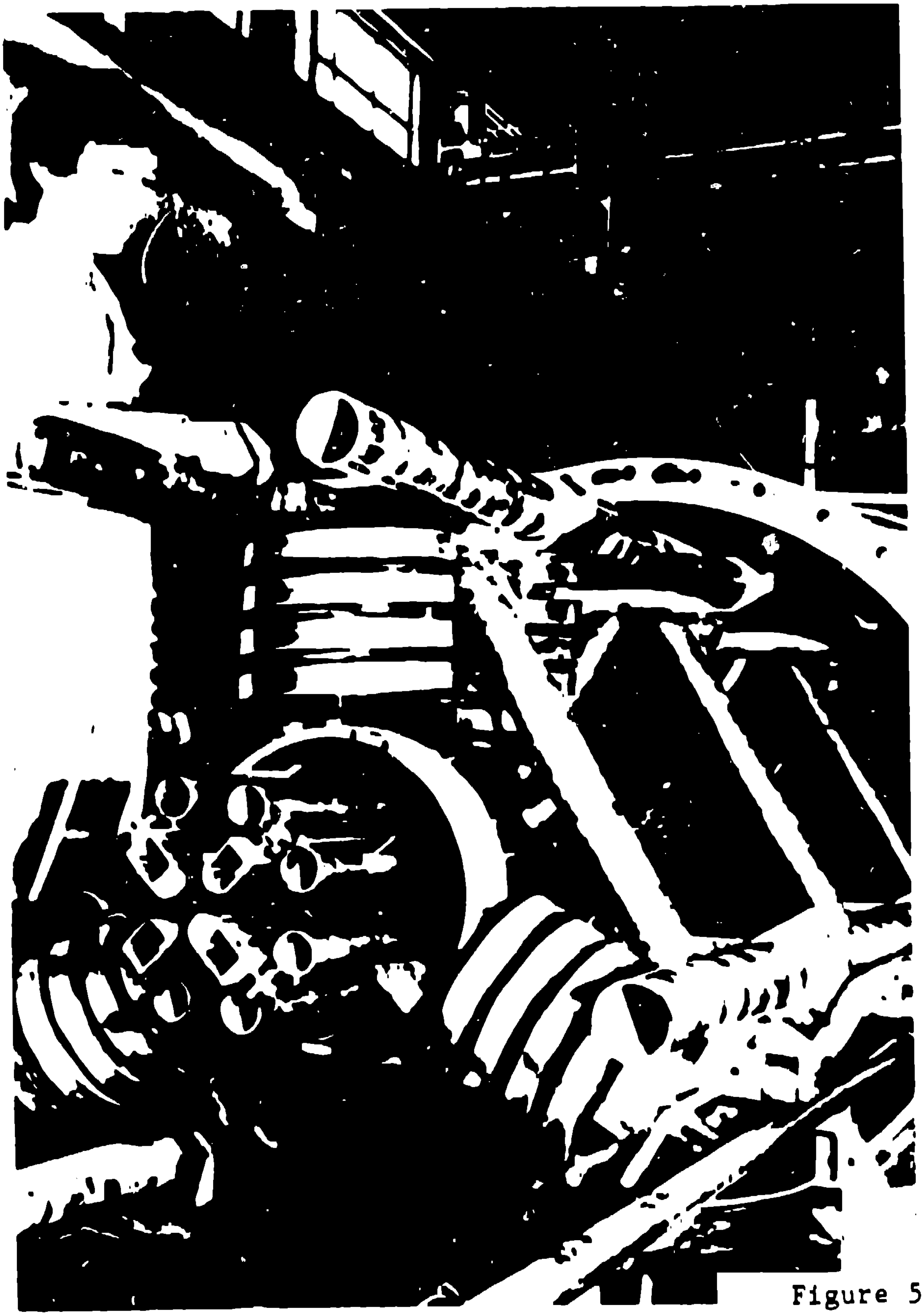


Figure 5B

Focusing (by) Axially Symmetric Accelerating Field (FASAF), and Fast Wave Focusing (FWF)

A third alternative to the RFQ and AAPF is proposed in a 1982 paper [BGMRS 1982] and again in an almost identical 1984 paper [BGMS 1984] in which ions are accelerated and focused by the rf field itself. Different kinds of focusing by an axially symmetric accelerating field are unified in the scheme, called FASAF. Transverse stability is provided to the particles being accelerated by those spatial harmonics of the accelerating field whose phase velocity is not equal to the average particle velocity (non-resonant harmonics); in practice the use of one such harmonic is sufficient. The required values of the amplitude and phase velocity of the focusing harmonic can be obtained by periodic variation of the drift tube gap synchronous phase, field or transit angle, and of the cell multiplicity. The focusing harmonic can have a phase velocity either larger or smaller than that of the accelerating harmonic, and these two cases are analyzed. If the ratio $k=\beta_f/\beta a$ (where β_f and βa are the relative phase velocities of the accelerating harmonic and the focusing harmonic) equals 1/3, the "self-focusing" accelerator results, discussed in Vlasov's 1965 book. For k = 1/2, the AAPF system results, realized through the asymmetry from the alternation of long and short drift tubes. Compound periods of AAPF result for 1/2 < k < 1; these periods give a relatively high capture coefficient for a given accelerating-field intensity. The case k=2 with π and 3 π between gaps does not provide APF. The case k=3 is important. Because of the odd harmonic relationship, the alternation of long and short drift tubes is unnecessary, the transit phase of the equilibrium particle remains constant at the gap centers, and the gap field amplitude can remain constant, so this version has no features of APF. This version, which is named fast-wave focusing (FWF), makes it possible to lower the injection energy of the ions. The FWF accelerator has a conventional appearance, Fig. 6, but requires the phase between gaps to be greater than π. Values of 1 < k < 3 correspond to compound focusing periods. The design of Fig. 6 is for k=3, and is based on a 150 MHz quarter-wave resonator to accelerate protons from 45 keV to 2 MeV in 48 cm using a gap field of 19 MV/m. The resonator diameter is 32 cm and the bore is 7-12 mm. The transverse and longitudinal acceptances are both quite

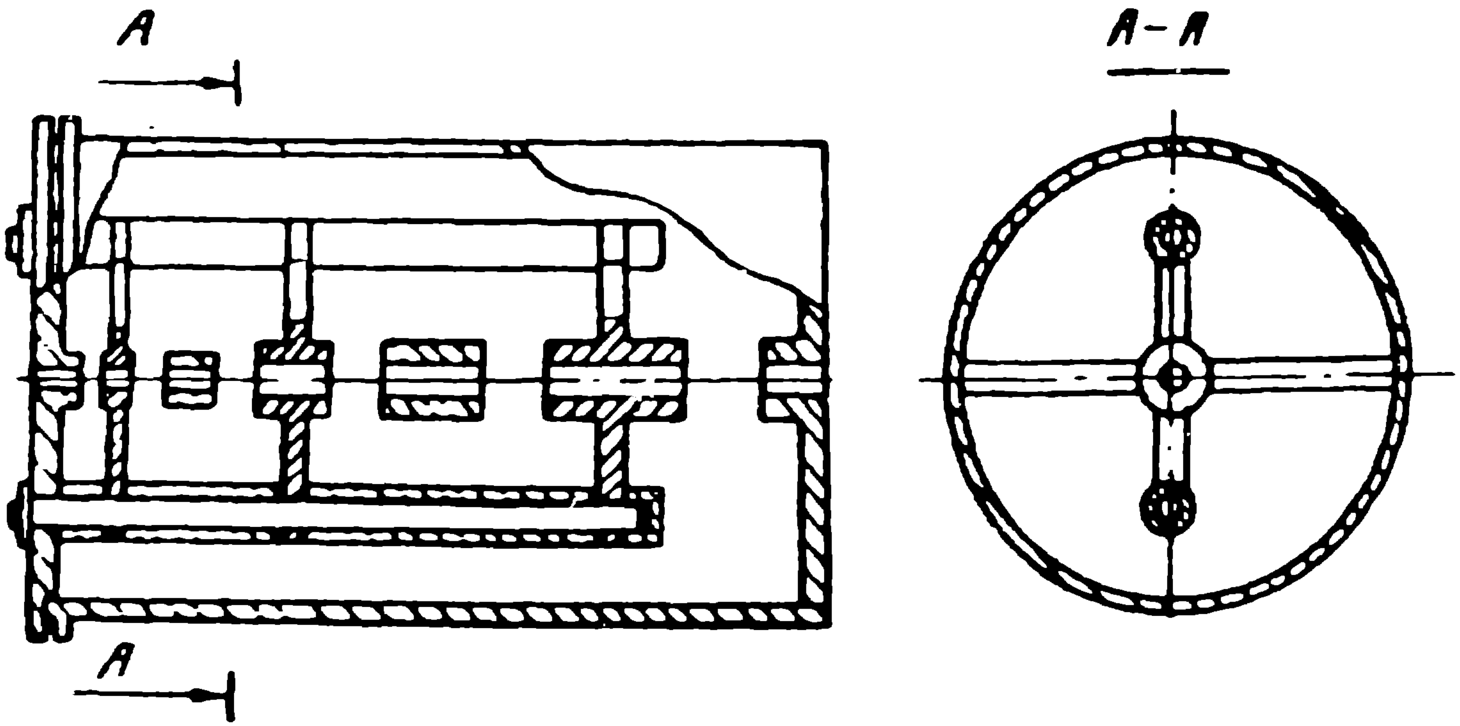


Fig. 1. Design of an accelerating section with fast-wave focusing.

Figure 6

adequate. The merits of the approach include design simplicity, high acceleration rate (up to 4-5 MeV/m), capture up to 180° and low injection energy.

This paper is very good -- an example of innovative thinking that provides a construct in which previous ideas like AAPF are included, and also derives a new useful case where k=3. This case might prove useful for flexible heavy ion machines; the example mentioned is for charge/mass ratios up to 1/12. Analysis of this scheme has yet to be undertaken in the West.

Work on this concept and on multibeam structures continued at the 10th All-Union [V 1986 (Sess.4.13), P 1986 (Sess.4.19), A 1986 (Sess.4.10)].

Structures for Ion Energies ~ 2 MeV to ~ 100 MeV

Innovative work occurred at IHEP for their URAL-30 machine during the 1970's on accelerator structures for this energy range. As described in [Wells, 1982], the main accelerator section (MAS), shown in Fig. 7 (from Wells Fig. 23), has a cross-section, gap, and horned focusing electrodes quite different from the Alvarez drift tube linac. The URAL-30 operated at 148.5 MHz, 30 MeV, 100 mA of protons, with a specified output emittance of 0.5 - 1.0 π cm•mrad. The MAS is about a factor of three smaller in diameter (resulting in a more rigid structure) than the Alvarez resonator, has a higher shunt impedance up to $\beta = 0.15$, and was found to be technologically and structurally simpler. The electrodes were welded to the resonator by a special technique guaranteeing alignment within 30 to 40 microns.

Nothing concrete was found in the literature search on further development of the MAS structure since 1982. Three titles [D 1983, D 1983, VPSC 1984] suggest that Inst. Yader Issled has done some work in this area. At the 9th All-Union in 1984, there are two papers [BBGGKSTS 1984, BBI 1984] by IHEP treating the problem of making field measurements by bead perturbations on axis, with an analysis of systematic errors, advantages to be gained in data reduction if the analytical form of the desired field distribution is known, and showing the experimental setups

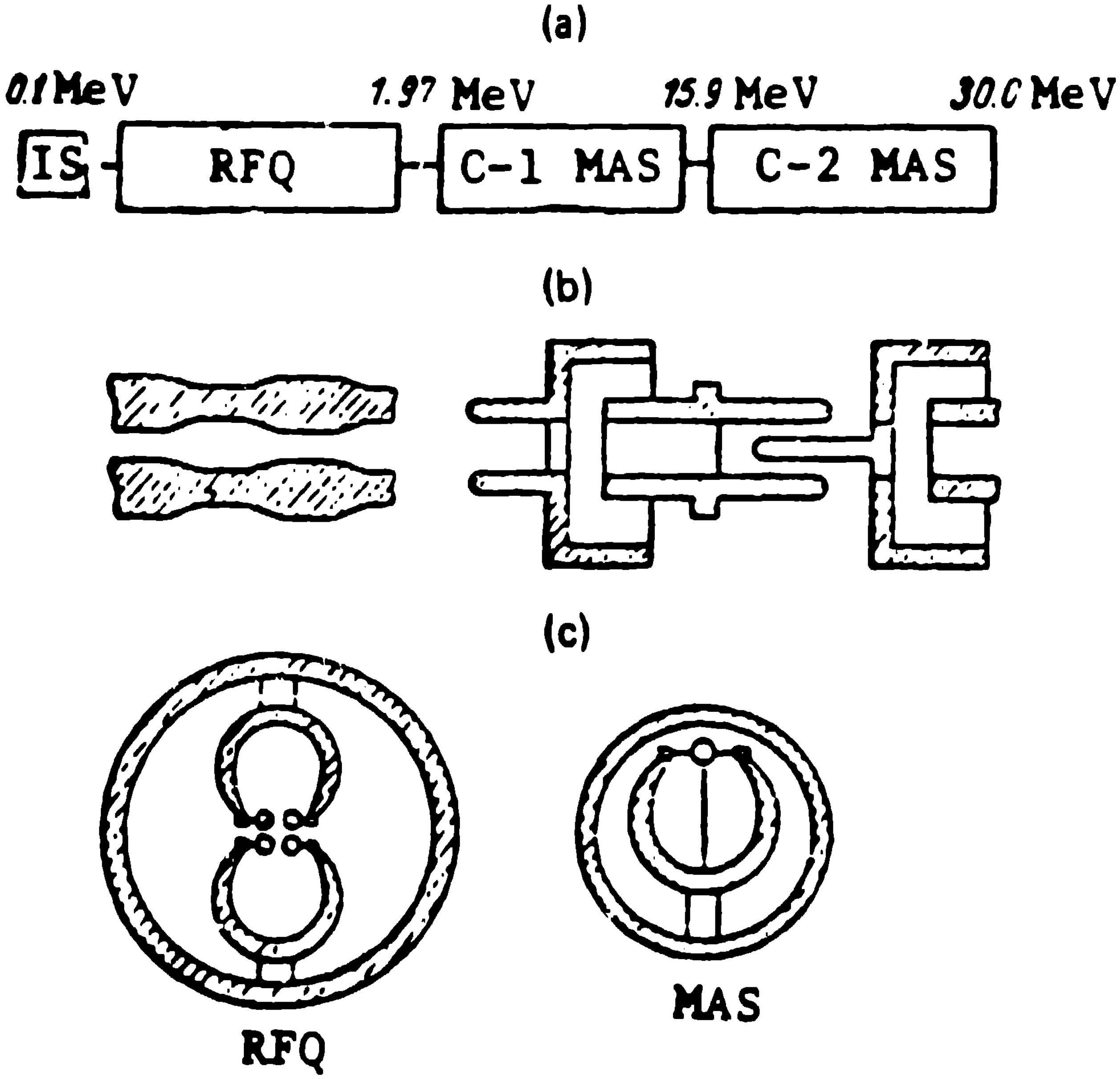


Fig. 23—Block diagram of the URAL-30 accelerator (a), electrode shape (b), and cross-section of the resonators (c) [31]

with computerized data acquisition and reduction. The linac used to check the test development results was their "high-frequency quadrupole focused" linac with "horned" drift tubes; presumably the URAL-30.

The high-brightness requirement for NPB has resulted in a frequency choice of 425 MHz for the ATS, as explained above; the Alvarez DTL structure diameter at 425 MHz is about three times smaller than it would be at 150 MHz so the ATS DTL has about the same outer diameter as the URAL-30 MAS at 150 MHz. Because the engineering requirements for eventual cw operation must always be kept in mind, it is not obvious that the MAS type structure would be preferred. It is clear, however, that Soviet innovation and test of experimental apparatus in this energy range was funded; although their MAS developments have been known to us for a long time, the difficulty of achieving well-balanced R & D programs in technology areas has precluded any parallel development in the U.S. Tune-up of a DTL is mentioned in a title [B 1986 (Sess.4.18)] at the 10th All-Union.

Structures for Ion Energies Above ~ 100 MeV

The LAMPF proton linac is still the only operating linac that accelerates protons into the energy range above around 100 MeV where transition into the coupled-cavity type structure is required The side-coupled structure SCL was invented for LAMPF. It is also an appropriate standing wave structure for electron linacs with pulse lengths longer than a few μs, and has remained the circuit of choice in the U.S. for electron applications. The SCL has a reasonably high coupling factor, which gives good field stability in the structure when carefully tuned, and the accelerating mode is in the lowest passband of the structure, which helps insure against the excitation of spurious modes.

The MEGAN meson factory was conducting design work during the construction of LAMPF, and invented a structure, called the disk-and-washer (DAW), having an even higher coupling than did the SCL, that was adopted for MEGAN. The goal of higher coupling was also sought by US researchers at Los Alamos, and the DAW was investigated during the early 1980's for application to advanced electron machines for nuclear physics research. It was discovered, apparently at about the same time in the US and the USSR, that the DAW, in which the accelerating mode is in an upper passband, was plagued by spurious modes. Design work to suppress these modes, without compromising other desirable aspects such as the shunt impedance of the accelerating mode, required tedious experimental work, or three-dimensional computer codes that were not available. Work on DAW's was therefore terminated at Los Alamos because of project schedule constraints, but with some progress made and enough understanding of the problem to point out that the DAW is still a future candidate for some applications when 3-D codes became available as was anticipated. The USSR, being committed, had to solve the problem, and apparently has done so to their satisfaction by introducing T-shaped slots into the washers which break the symmetry of the most offensive modes [ABYKP 1982]. Work in Japan produced another variation for symmetry-breaking. Two papers (YKPR 1984, GP 1984] at the 1984 9th All-Union show work at the detailed level to specify manufacturing tolerances for DAW parts and on algorithms for approximation of the dispersion curves, and results of module tests at high power are given at the 10th All-Union [E 1986 (Sess.4.10)].

Work has also continued at IHEP on development of the bridge couplers used to incorporate space for focusing magnets in a multi-tank section driven from a single amplifier. [DPRR 1984, DPPRR 1985].

Because of the proven effectiveness of the SCL and the probability that an improved DAW would also work, basic development work to accelerate light ions beyond 100 MeV is not absolutely required for envisioned NPB applications, although improvements in system efficiency would be sought and advanced engineering for space basing needs to be done, and some important new work is being done in the USSR.

At the 8th All-Union, KhPTI [BVOK 1982] has a vary interesting report on a new type of accelerator structure for high-beta particles. The objectives of the research were to eliminate the complicated structural aspects of the SCL and DAW so that fabrication and tuning would be earlier, and to afford better cooling that on the DAW, where the disks are supported on stems. The result is structures with no axial symmetry, Page 16.

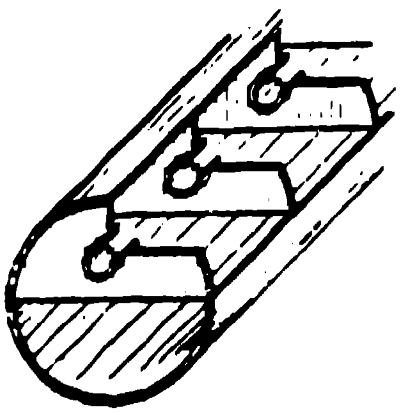


Fig. 1.

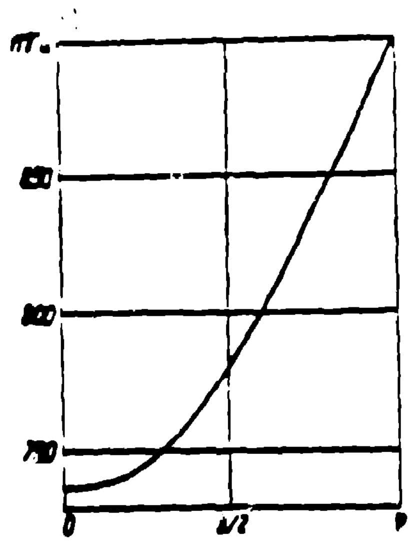


Fig. 2.

Fig. 1. Diagram of structure with one-sided location of segments.

Fig. 2. Dispersive curve of structure with one-sided location of segments.

Key: (1). GHz.

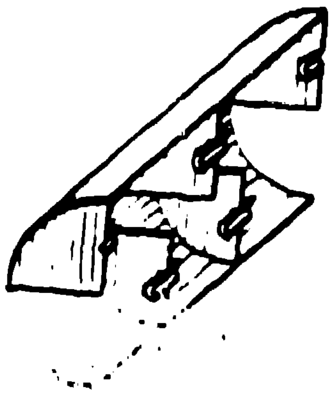


Fig. 3.

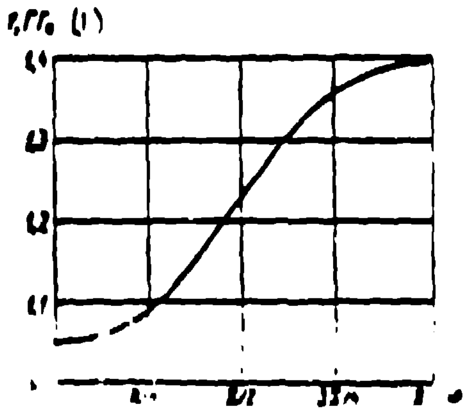


Fig. 4.

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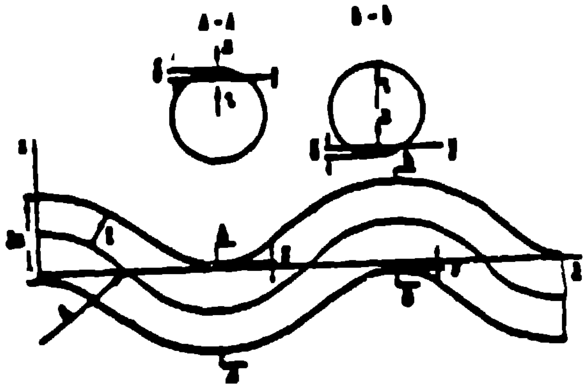

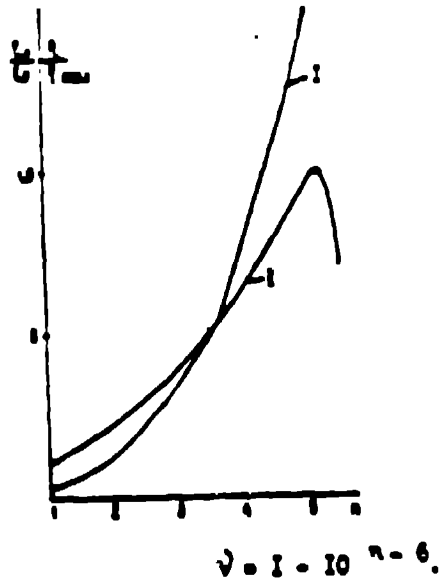

Fig. 1.

Fig. 2.

Fig. 1. Accelerating structure.

Fig. 2.

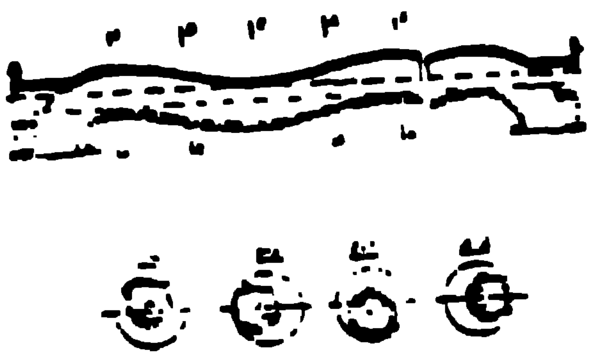

Fig. 3. Structure for accelerating continuous electron stream.

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From solution of (3) it is evident that wave amplitudes have as shown in Fig. 8. The structure coupling is obviously large, quoted as 30% for the two-beam case. The single-beam, one-sided structure is quite different from ordinary structures in that the π-mode has the largest group velocity and mode separation in the passband. The $\pi/2$ mode has maximum group velocity in the structure with alternative segment locations. These structures should be investigated in the West. This innovation and the work on sinusoidally bent waveguide structures for electrons described in the next section again show the imagination that the Soviets have brought to accelerator structure design. This kind of work requires deep understanding and sustained work. It seems almost certain that part of the reason for the continued emergence of such ideas would be that accelerator R&D is a recognized goal that is deemed worthy of stable funding at several key institutes. In the U.S. there is almost nothing of this sort; projects must be constantly proposed on a yearly basis and basic accelerator research is rarely funded on its own merits but only if it relates to a near-term project.

Electron Linac Structures

This report is not intended to cover electron linacs, but the synergism in the high brightness accelerator technology for ion and electron rf linacs is very strong, so it is useful to note that the USSR also has the full range of electron machines and techniques. This includes continuous wave microtrons, application to free electron lasers (requires high-brightness electron linac), and application at x-band for radiography (requires detailed understanding of accelerator structure limits). The references listed are not exhaustive.

NII with Tomsk Polytechnic Institute [DFS 1982] discuss a sinusoidally bent waveguide structure, Fig. 9, to accelerate electrons (a continuous stream can be accelerated if desired.) The advantage of the structure is that the ratio of peak surface field to accelerating gradient (the overvoltage coefficient), at the point of corresponding values of the ohmic losses, is six times less in this structure than in the usual diaphragm-type electron linac structure. This should allow a higher accelerating gradient to be attained. Transverse beam focusing in this structure is discussed at the 10th All-Union [M 1986 (Sess.7.1)].

A 1986 title and abstract from RTI [L So 1986] is quite interesting for two reasons, one that RTI appears to be publishing significant work after a period of silence, and second because the technical subject, deceleration of relativistic electron bunches, is interesting in terms of energy recovery operation of a FEL and also as a linac power source. This paper is discussed further under rf power sources.

RF Field Breakdown Limit

Pushing to higher fields in accelerator structures before breakdown occurs is an important research area where progress would benefit all applications.

Two papers discuss rf breakdown levels at the 8th All-Union. Yetremov Institute [VGIPRSSTT 1982] believe the structure length is a factor, and quote, at 3 GHz, peak surface field of 150 MV/m, pulse length $\tau=2\mu s$ on a short standing wave structure, 180 MV/m, $\tau=4\mu s$ and overvoltage coefficient = 3.8 for a meter section of septate waveguide in a hf-separator, and 33 MV/m, τ = 10μs for a section with overvoltage coefficient = 3.3. They find that in real long accelerator structures the rate of acceleration usually does not exceed 10-15 MeV/m, and state that it is completely obvious that prototype testing would be required to go higher. They tested a one meter section of diaphragm-loaded (SLAC-type) waveguide in both traveling and standing wave modes, the material was oxygen-free copper with surface finish characterized by a 25μs finish, silver soldered in vacuum. In traveling-wave operation, 3μs pulses, the average acceleration rate achieved was 20 MeV/m, with maximum acceleration rate in the central cells of 30 MeV/m and peak surface field of 40 MV/m. In standing wave operation, the structure had a mean accelerating gradient of 10 MeV/m, accelerating field in the waveguide cells of 30 MeV/m, and peak surface field of 50 MV/m. They infer problems with the magnetron drive and say there were almost no breakdowns, so these are not limiting values. Their conclusion is that accelerating gradients of 100 MeV/m at 6 GHz for VLEPP should be possible. INP of SOAN USSR [BBBBZI, et al 1982] cites achievement at 3 GHz of 150-200 MV/m peak surface fields in a single cell. At 6 GHz, in a 29 cm section with 14 resonators, 0.8μs pulses, 55 MeV/m was achieved with the electron beam being accelerated, before the limit of the rf amplifier was reached. Work reported at INP, Novosibirsk, in the 3-6 GHz range cites the achievement of a 90 MeV/m acceleration rate and 150 MV/m peak surface electric field in the VLEPP structure (electron linac type). [BBBZIKKKKKNOPSSKYY 1984, BBZKKKNSSYY 1986]. This is equivalent to levels achieved in the U.S. Continuing work is discussed at the 10th All-Union [B 1986 (Sess.6.13)].

Permanent Magnets

The use of permanent magnets has many advantages for many of the beam focusing and transport magnets used in accelerator systems, including the quadrupoles in DTL's, and dipole up to multipoles as high as necessary for beam transport. Permanent magnet materials afford high magnetic strength in confined space without the need for electrical connections and with significant savings in overall system weight for many of the small to medium bore magnets required. (For large bore magnets, electromagnets may be lighter.) Another advantage is that modern materials such as samarium-cobalt or neodymium-iron are so nearly perfect that design can be done using the superposition principle -- the fields from each block of material don't affect each other. The prospect of using permanent magnets is a very old idea, but suitable material has only been available for about the last decade. After U.S. papers began discussing permanent magnet quadrupoles in DTLs, a dramatic incident occurred at the next U.S. Particle Accelerator Conference when USSR representatives strongly argued that the scheme had been invented there first. Permanent magnets are now routinely proposed. ITEP reported in 1980 on quadrupoles "with poles of implicit form" created from wedges of material; the same as the U.S. technique. [GMRS 1980]

Superconducting Structures

Superconducting structures have been developed for both ion and electron beams and might eventually be useful for high-intensity high-brightness beams if it can be learned how to prevent even very small amounts (nA per meter) of beam from being lost along the linac, because such losses would drive the structure normal and spoil its properties. In the meantime, superconducting structures are beginning to find important applications at low beam intensities, because significant progress in their development within the last few years has made gradients up to around five MeV/m routinely achievable.

At the 7th All-Union, Yefremov [VVKKOSSSC 1980] describe a program designed to solve an entire group of problems related to the creation of superconducting high frequency accelerators and the production of high-quality, monochromatic electron beams, using equipment for full-scale operation.

Development reported at the 1984 9th All-Union included work at SRINP with the Tomsk PI on dismountable niobium 9.5 Ghz cavities. [DAKNSY 1984] With electrochemical treatment of the working surfaces, but without high-vacuum, high-temperature annealing, Q's from 10^9 - 10^{10} and peak fields of 0.95-0.12T (20-25 MV/m) were achieved routinely. Attention was also given to contacts and dismountable waveguide, using cavity field computations to design for a zero azimuthal magnetic field at the joint site. They conclude that manufacturing techniques are mature enough to consider use of superconducting structures with choke coupling in electron linacs. On the other hand, investigations at the Yefremov Institute [KOSST 1984] and the INPSOAN (Novosibirsk) [ABVVKPPSF 1984] stood at Q's of a few x 10^3 and fields of 4.5 MV/m for cw operation and 8 MV/m for 20-50 ms pulses, and the general discussion of new generations of electron accelerator for nuclear physics [B 1984] concludes that superconducting linacs are still economically unpromising. This situation parallels that of the West around this time; the SRINP achievement of 25 MV/m, if true, was as good or ahead of any performance reported elsewhere, but applications such as the proposed CEBAF were still using room-temperature techniques. CEBAF switched its design to superconducting in 1985-86.

At the 10th All-Union, two invited talks [N,M 1986 (Sess.13.2 and 3)] were given on advances in the production of superconducting materials for accelerators and on the problems of protecting superconducting materials from radiation, and equipment and methods for measuring the electrodynamic characteristics of superconducting structures were discussed [A 1986 (Sess.4.26)].

A related technology is the exploration of structure Q enhancement by factors of ten or so gained by operating the structures at cryogenic (but not superconducting) temperatures. This may have advantages for space-based system where the environment and availability of large amount of coolant are important factors. No mention of work along these lines was found.

BEAM DYNAMICS

Computer Simulation Codes

There seems to be a fairly strong belief that the Soviets lack significant computing power and therefore fall behind U.S. technology. In accelerator technology, this may have been true in the early to middle 1970's, but there is little evidence of any lack today. It is possible that the computers themselves may be more limited, but as with any tool, often more depends on how it is used. It was clear in the late 1970's that good use was being made.

At the 7th All-Union in 1980, IHEP, in collaboration with INR and INP, Novosibirsk, was operating the U.S. program SUPERFISH, developed around 1976, for finding resonant frequencies and other information required for accelerator structure design [ADKPSS 1980, PSS, DPF, KDFY 1980], and had made their own modifications to the software. INP used its own programs FAST, LONG and FINI to model axisymmetric laminar beam dynamics in single particle approximation for the VEPP-4 positron source. [KKLNOSFYY 1980] Better accuracy for intense beam interactions with actual boundary conditions was achieved with the program MASON, using the finite elements method with a set of cylindrical macroparticles to solve Poisson's equation. These programs gave answers within 10% of experimental results where about half of the injected beam was being lost in the structure. The output beam was too large vertically, and beam-breakup problems caused by the resonator coupling slots were suspected.

The MEPI paper at this conference [AVKP 1980] is remarkable. Titled "Intellectual Automated System for Planning Charged Particle Accelerators," it discusses the development of models for accelerator design under the mantle of an artificial intelligence format, although with the statement that the AI part was somewhere in the future. Three models are outlined for computation of static fields, eddy fields in closed volumes with conducting surfaces (wave guides and resonators), and intense charged particle beam dynamics. The problems of self-consistent combination of these models was being addressed, as were the challenges of multi-parameter optimization. It is not clear that this work was part of an overall plan. Such an approach was imagined at some U.S. centers in those days, but the strong tendency toward funding by projects or to user-oriented operational facilities where machine innovations were resisted left the broad-gauged approach to systematic improvement and integration of techniques largely by the wayside until the present interest spurred by SDI, where control is a key issue. The point is that this kind of integrated approach could have significant impact on the design of the complex, highly optimized systems imagined today.

In 1982, IHEP had written its own cavity mode program PRUD-O and claimed its was two orders of magnitude better than SUPERFISH in the accuracy of the mode frequencies and also ran faster. [ADYPRR 1982] IHEP, INR, and MEPI [GIKF,KK 1982, BST 1982] gave details of their programs, including MULTIMODE, which did not require a frequency spectrum seed solution as SUPERFISH did.

By 1984, both PRUD-W and MULTIMODE had been extensively developed and detailed descriptions were given at the 9th All-Union. PRUD-W had been extended to handle the non-axially-aymmetric modes of axially symmetric resonators, periodic structures via the Floquet quasi-periodicity approach, and certain interruptions in periodicity related to bridge couplers. PRUD uses eight-node isoparametric elements, with subspace interation for the algebraic solution of eigenvalues. In a paper on cw microtrons [GGINPSSSSS 1984], mention is made of computational techniques, including the use of internationally available U.S developed codes like TRANSPORT and TURTLE.

IHEP [ADEPRR 1982] describe their code FEMB 12 for computing magnetic fields in complex magnetic circuits containing materials with differing permeabilities. They claim their code is 3-5 times more effective that the U.S. standard POISSON code group for nonlinear problems (where the pereability varies with field strength), and 10 times for linear problems, but that the biggest advantage of their method lies in the possibility of calculating stray fields in magnets with open-circuited magnetic circuits, such as septum magnets.

Progress on the MEPI automated design project is presented again. The programs are oriented to the YeS EVM Unified System of Computers. Overall access is through a program called PRIMUS, that allows interfacing with a variety of terminals and computers from other organizations, and allows use of software packages of many kinds, including ones foreign to MEPI, such as POISSON or PRUD. It is stated that the power of PRIMUS results in poor interactive time response, so machine-dependent versions of the interface and supervisor programs have also been written. Drift tube design is incorporated, including procedures for APF, where the gaps and tubes have a complicated p ttern of different lengths. A Monte Carlo method is used to incorporate the real details of drift tubes (corner radii, etc.), and this method also allows the "modest" computation of 3-D fields in RFQ structures, in an integral equation context. Routines are incorporated to optimize cavity shapes from a description of the desired fields (inverse problem of electrodynamics), to compute particle beam dynamics including space charge, and to do beam breakup calculations. Considerable attention is given to the optimizer routines. The programming is structured to afford convenient updating and changes. The full use of beam dynamics simulation programs is evidenced in discussions of VLEPP and MEGAN at the XIIIth International Conference on High Energy Accelerators [BN 1986, YPS 1986, SS 1986]. Modeling of fields and particle dynamics in axially non-symmetric structures [B 1986 (Sess.7.30), optimization of resonators (S 1986 (Sess.4.11)], and 3-D structures code work [M 1986 (Sess.4.12), A 1986 (Sess.4.15)] are mentioned in titles from the 10th All-Union Conference.

Beam Dynamics Theory

The Soviets have a long-standing reputation for excellence in the theoretical realm, possibly bolstered in previous decades by not being able to proceed immediately to hardware. However, much of their work parallels that of the West, and it is not clear that their facility with the tools of theory has resulted in any edge. In some cases, the clarity of a good theoretical model probably helped produce a breakthrough; for example, this may have been the case for the RFQ, where the underlying theoretical principle is in fact very simple. A reading of the reference titles assembled under this section covers the full range of topics and applications that one would find at the U.S. Particle Accelerator Conferences, at a generally equivalent level.

One new result may be of use in the procedure for tuning the rf field amplitudes and phases of the modules of a high-beta linacN At LAMPF, the Δt procedure was invented for this purpose. MEGAN faces this tuneup problems in the future, and INP [DL 1982] have devised some enhanced procedures which may be more accurate.

Titles of possible interest on measurement techniques at the recent 10th All-Union include a phase spectrum measurement using secondary electrons [V 1986 (Sess.7.31)], and a discussion of the basic principles of constructing and investigating structure models [Z 1986 (Sess.4.27)]. (Aberation in magnetooptical systems is given as a title (A 1986 (Sess.7.34)] at the 10th All-Union. ** This should be moved to the Beam Transport section **)

High-Brightness Beams/Emittance Control

The concluding statement at the 7th All-Union observed that "reported programs of calculations generally refer to beams with high intensity and would be applied in other acceleration centers." It is apparent the USSR accelerator developers have been interested in high-intensity effects for many years. The theoretical work of Vlasov is a fundamental underpinning of this area. As outlined in the introduction, there are two major areas of interest for high brightness beams: the non-relativistic regime, covering most ion beam applications and electron beam sources, where the self-repulsion effects of space charge and the nonlinear interactions of the space charge with the external fields are important, and second, the relativistic regime where beam breakup effects from the interaction of the beam with its surroundings are important.

Space-Charge Effects

In the past, Soviet theorists contributed significantly to the physical description of high-intensity beams through the nonlinear Vlasov equations, that relate beam dynamics and the particle phase-space density distribution function, and the Kapchinsky-Vladimirsky (KV) equations that constitute a linearized set of equations of motion for the envelope of a beam in a focusing system, where the particle distribution, called the KV distribution, has particles distributed uniformly only upon the surface of the phase-space hyperellipsoid, resulting in the linear equations when projected on to a transverse plane. Stimulated by the heavy-ion fusion program, extensive analysis was performed at LBL on the KV distribution in periodic focusing systems, and instabilities up to sixth order were identified as a function of the tune depression, or amount of space charge present in terms of the ratio of the phase advance through the focusing period with space charge to the phase advance without space charge. The non-physical shell nature of the KV distribution is the driving term of most of these instabilities but it was found that some realistic distributions exhibited emittance growth at approximately the same tune depressions, although lower limits on the tune did not apply to the realistic distributions. Other work at Los Alamos using computer simulations found that the addition of (reasonably gentle) acceleration did not alter the situation radically, and proved that the energy balance between the phase space dimensions was an important quantity, that, if balanced, allowed large tune depressions without emittance growth. Subsequent work at Los Alamos has revealed important aspects of the way that excess field energy in the phase-space distribution can result in emittance growth.

The papers found in the literature search show a full capability for studying the effect of space charge by including space charge in the beam dynamics simulation codes, using particle-in-cell or direct Coulomb interaction routines in the same manner as the rest of the world. However, there is essentially no evidence of significant work on the basic physics of the effects of space charge on beam brightness, except for a 1982 ITEP paper by Batalin. [B 1982]. As was tried in the early 1970's by Lapostolle at CERN, Batalin attempts to use an entropy production approach to find a space-charge "friction" coefficient and a kinetic theory of transfer phenomena. He shows that space charge combined with transverse velocity spread leads to transverse emittance growth when the beam is mismatched to the focusing system, and that synchrotron oscillations produce growth in the longitudinal plane. Separating the interactions into short-range and long-range parts, he shows that the entropy increase during a transverse period for a KV beam is zero if the beam is matched but non-zero if mismatched, even for a continuous channel, and gives a single-particle estimate. At this point, he needs a connection between the concepts of entropy and emittance, but finds this impossible in general, so uses the rms emittance and derives an emittance increase across a period containing a crossover. The formulae and proportionality relations give the qualitatively correct results that emittance will increase if the input beam is mismatched, that the growth is faster at lower energies, and that there is a strong dependence of the growth on the magnitude of the initial emittance. He states that for quantitative comparison with experiments, the phase oscillation contribution per period would also have to be accounted for, and cites the need to set up specific experiments. The analysis fails, as did the earlier entropy based analysis, in providing anything beyond qualitative agreement with observed behavior. A paper with nearly the same title was submitted but then withdrawn from the 1984 Linear Accelerator conference at Darmstadt, but provided as a preprint.

This is one of the areas of accelerator technology in which the absence of published work of the Moscow Radiotechnical Institute during the late 1970's and early 1980's is most striking. RTI did most of the design work for the high-intensity MEGAN meson factory and exhibited the most advanced capability for overall accelerator development and understanding of high current rf linacs except for Kapchinsky at ITEP. However, no published work was found from 1980, until 1986, when two titles and abstracts [BD 1986, LSt 1986] from the XIIIth International Conference indicate that RTI is indeed fully up to date, as would be expected. In [BD 1986], qualitative relations are obtained from analysis of a large number of numerical experiments that associate the current density and beam emittance with a matched value of the magnetic field induction. The mechanism for emittance increase is identified as the difference of potential energies between the initial beam and a steady-state beam with a uniform charge density. Relationships are given for estimation of the emittance increase in a matched regime. In [L St 1986], the rapid initial redistribution of an initially nonequilibrium distribution to a distribution close to equilibrium is described by thermo-dynamic type radial force balance equations, allowing prediction of the steady-state distribution that an injected beam will move toward, and the steady-state temperature that will result. Titles [Y 1986 (Sess.7.9), B 1986 (Sess.7.10), D 1986 (Sess.7.14), B 1986 (Sess.7.24), B 1986 (Sess.7.26), A 1986 (Sess.7.33)] from the 10th All-Union suggest that considerable work toward understanding space-charge effects is in progress.

Beam Breakup (BBU) Phenomemna

At higher ion energies or in intense electron accelerators, the abrupt entry of beam packets into the resonant cavities shock excites a large number of cavity modes, generating fields that can then affect the motion of the following particles in the same bunch, or even in a following bunch. The most harmful of these fields are those with transverse components that can steer the beam or increase the beam emittance; if strong enough, the beam can be steered into a wall or expand and be scraped off. These effects are called beam breakup (BBU) phenomena, and have been the subject of intense study in recent years, especially for high energy physics beam collider machines, but also wherever intense, relativistic beams are needed.

At ion energies of interest for NPB, the currents that can be accelerated in single channels are below the threshold levels for BBU effects. This was estimated for LAMPF and has been verified by the operation of LAMPF and other linacs where the peak was considerably higher than LAMPF's.

At the 1984 9th All-Union, INR [YO 1984] presents an analysis of a resonator chain including axially asymmetric modes and the transient effects, and covering the conditions were the beam interacts resonantly with a transverse mode and where the beam is off-axis. The results indicate that the intended beam current and other parameters of the meson factory accelerator are also safe from BBU effects. MPEI [BZST 1984] has created similar models and discusses the development of a FORTRAN-4 computer code KRAB for YeS series computers (requires 250 kbyte storage) which calculates the electric field amplitudes and phases of azimuthally uniform modes excited in axisymmetric resonators by modulated or unmodulated particle clusters. An optimization routine KROP minimizes the effects by changing the resonator geometry, requiring about 40 minutes per run. Experimental verification was performed with beam through a three-cell resonator. One way to attenuate undesired modes is to break their symmetry patterns; an analysis of the use of slots in the connecting walls of resonator chains is developed by the Yefremov Institute [O 1984]. The techniques available to the Soviets for BBU analysis and simulation appear similar to those of the rest of the world; this area has received extensive international attention because of its high relevance to high-energy physics research accelerators. Recent titles [A 1986 (Sess.7.4), B 1986 (Sess.7.12), K 1986 (Sess.7.16) at the 10th All-Union indicate continuing research into BBU effects.

RF POWER

An advanced method for producing rf power for a linear proton accelerator is discussed in an RTI paper [L So 1986] at the XIII International High-Energy Accelerator Conference. A bunched relativistic electron beam would be decelerated in the linac structure and would produce rf power in the accelerating mode, which would then be used to accelerate the protons. Some special aspects concerning phase stability and possible instabilities are noted, and a numerical study is cited in which 90% of the energy of a 2 MeV, 16 cm wavelength beam of several tens of amperes was recovered. A klystron oscillator with external synchronization is mentioned in a title from the 10th All-Union [B 1986 (Sess.4.20)]; successful use of synchronized oscillators might offer important system advantages. The important subject of the interaction between the accelerator structure load and the rf power source is discussed in two Yefremov Institute and LEIU papers at the 1984 9th All-Union. The form is derived for the scattering matrix of a matching device between generator and load that will enforce requirements during the transient stage of pulsed operation [VM 1984] or that will insure stable starting of a self-oscillating magnetron system [VMP 1984]. Optimization of system power characteristics for circular machines [BVKM 1982] and for short electron pulses [BK 1982] were discussed at the 8th All-Union in 1982. Rigorous understanding of the amplifier-load characteristics is an essential part of providing the tight control of field amplitude and phase in the accelerator structure for high-brightness beams, and could have a significant impact on system aspects; for example, heavy isolators might be avoided by sophisticated design. Thus this area of rf engineering is required for advanced systems and there is clearly a USSR capability. Titles from the 10th All-Union indicate continuing emphasis on the overall system aspects of the rf power and accelerator structure elements, in terms of setting the amplitudes and phases in a multi-resonator system (MEGAN) [E 1986 (Sess.4.5)], and load compensation [M 1986 (Sess.4.8)].

AUTOMATIC CONTROL

Fast Hardware Stabilization

Rf accelerators work on the microsecond time scale, so the rf field amplitude and phase controls, resonance controls, power supply regulators and other equipment are built using closed-loop systems based on modern control theory principles. The Soviets have this capability, evidenced in papers discussing controls for MEGAN [NOPSVS 1980, KKPY 1984] and for the IHEP linac with quadrupole HF focusing, where beam currents of 150 mA or more are compensated with a nonlinear system with a response of 0.5 - 0.7 μsec.

Automation of Diagnostic and Measurement Systems

Computer control of field amplitude measuring systems and other laboratory procedures is discussed in [AGGKRTS 1984], [GKZ 1984], [S 1986 (Sess.4.16)].

Automatic Control of Systems

Overall control of entire accelerator systems, from off through standby and operational modes, with full recovery possibilities from various fault states, without human intervention, quickly and reliably in a harsh environment, is a major objective for space-based systems. To a lesser extent, the same objectives apply to large ground-based research or industrial machines. The Soviet literature shows that serious attention is being paid to this area.

The intelligent systems for accelerator design being developed by MEPI were discussed in a the section on beam dynamics codes. This system of programs would form a very important core for an automatic control system as well.

The Russians coined the term "cybernetic accelerators" for systems that they imagined would be ruled by integrated automatic control systems; the "investigation of the vast complex of problems, connected with the cybernation of accelerators --- was for the first time undertaken in the Radiotechnical Institute of the AS USSR" [VB 1984]. Orbit control in large circular machines by these methods has become de riguer world-wide [VBBVVGZ etc 1980, VKMS 1980, AZR 1982, VGKM, AGS 1984, ABVGZMOR 1980. ABZRS 1984] The [VKMS 1980] article shows thorough integration of techniques from the electrical engineering discipline of modern automatic control to the accelerator problem. (This cross-disciplinary approach is often missing in U.S. accelerator control systems, which tend to be implemented by an often uneasy consortium of physicists and computer scientists.) In this case, the drift effect of uncontrolled factors is tracked by an algorithm which looks for an extremum using a simplex search along the drift direction with simultaneous adaptation to the magnitude of drift velocity. ITEP [ABVGZMOR 1980] discusses a program that automatically optimizes injection and capture of the proton synchrotron (simplex method), adjusting up to 20 parameters of the accelerator.

In 1982, Yefremov Institute [BVVPSC 1982] gives a very interesting discussion about how they have implemented an automated system for their series of linacs, using their new SM-4 minicomputer. Contact with the operator is condensed into a dialogue, with yes/no answers to system queries and resulting setting of the machine to one of the preset operating modes or conditions. The operator can initiate directives form the keyboard of the type "establish," "regulate," "optimize," and so forth.

One important subsystem that has not been automatically controlled in the past is the ion source and injector. The main reason for this is that there was never a strong incentive to invest in the thorough engineering development of such injectors, even though their often quirky and unreliable operation have cost untold hours of unscheduled beam downtime. In space, however, the source must run unattended, and bringing it under automatic control is an important near-term objective of the NPB program. It is interesting to note the work being done at INR on the control of the MEGAN 100-KV injector [AVGGZK 1982], [AAKKSS 1984]. The 1982 paper contains a description of intended control system architecture and function to achieve completely automatic control, demonstrating a clear sense of the requirements and approach. A two-stage process is envisioned, however; the first would be a supervisory system, followed by the fully automatic one. Details of the proposed fully automatic adaptive stabilization of the beam intensity from the injector are given by Kiselev [K 1982] in the more rigorous construct of control system mathematics. He states that experiments were done on the actual equipment that verified the efficiency of the method under conditions of drift and in the presence of control-loop transport delays. This work, both in conceptual and analytical development as well as in experimental proof, is well ahead of present U.S. status. By 1984, some parts are running. Two Elektronica-60 computers joined by light links are used -- one on the high-voltage platform and one at ground. Control of electronic voltages, solenoid currents, pulsed valves, discharge chamber gas pressure and pulse timing is required. Automatic restarting of the injector after a high-voltage breakdown is provided. However, no details of closed-loop control of source parameters are given; rather, the system described for this H^+ (proton) source seems to be only supervisory in nature and similar to those pioneered at LAMPF and now used in all accelerator facilities. A proportionality large amount of attention is paid to control systems at the 10th All-Union, where one session is devoted to the topic and titles are found in other sessions as well. [N, V, K, B 1986 (Sess.2.22-25), B 1986 (Sess.3.3) B 1986 (Sess.4.9), K, N, V 1986 (Sess.7.40-42), G 1986 (Sess.12.16). These titles suggest the development of sophisticated algorithms, using modern control theory, not just routine supervisory data systems.

Summary, Conclusions, and Observations

An overview of high brightness accelerators shows the complex, multidisciplinary nature of this technology and outlines the linkages between the theoretical, experimental and engineering skills required and between the major system components.

Various observations and comments are made in context through the chapter. Overall conclusions include:

1) Overall, the Soviet accelerator community demonstrates an understanding of the basic principles, experimental work in developing these principles, and advanced tools in the area of computer simulations, relative to the construction of high brightness accelerators, that is on a par with Western capabilities. In particular, to correct a fairly widespread misconception, Soviet capability in computer simulation is quite adequate to the task, and code development is a continuing activity.

2) In some cases, the USSR capability and achievements tend to be ahead:

a) The Soviets have long excelled in finding new and practical accelerator structures that offer advantages in higher brightness or other system aspects. Recent work shows that they have a strong capability to build RFQs, but that they have also not neglected to continue looking for new approaches. Proof of alternating-phase-focused (APF) structures continues and has led to the innovative concept of fast-wave-focusing (FWF). Work on multiple beam structures has also been in progress for several years. A new form for the intermediate energy DTL has been studied. A very imaginative innovation for high-beta structures was announced in 1982. This work indicates a long-term point-of-view .

b) Automatic control of accelerator systems may be at a more advanced state than in the West. The Soviets clearly have a multidisciplinary approach that properly brings accelerator physics, modern control theory, computer science and possibly artificial intelligence (AI) together; in the West, the modern control theory aspect has not yet been brought to bear, and AI application has barely begun. This area is a crucial one for automated, space-based systems.

c) More attention appears to be paid to the interactions between the rf power system and the accelerator structure load.

3) The Soviet accelerator research program appears to have a strong continuity of effort, with accelerator research supported as a science in its own right. This approach, while not without its own hazards, is in marked contrast with the U.S., where funding agencies are project oriented and have an extremely short-term point of view. Even these projects are often redefined and rebudgeted several times per year; in this environment, it is almost impossible to balance near-term milestone requirements against long-term technology development. Another way of saying this is problems requiring a long

attention span get short shrift. Examples of the Soviet approach include the charter to develop superconducting accelerator structures to address a wide range of applications, the obvious long-term attention to innovative accelerator structures, funded computer simulation development, and sustained development of sophisticated automated design techniques and automatic control systems.

4) Experimental equipment development sometimes appears to occur slowly in the USSR; the example often used is their meson factory MEGAN, which has been under construction for a long time. However, this impression is also not completely correct. In their innovative accelerator structures program, there seems to be quite timely testing of the new ideas in hardware, often with actual accelerated beam. For example, the very large, 6 MHz RFQ at ITEP was constructed in a few years, comparable to U.S. schedules for a major piece of apparatus.